Eucalypts: Picking the Winners

A breeding objective for plantation eucalypts
and early-age selection towards this objective

by

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Declarations

This thesis does not contain any material which has been accepted for a degree or diploma by the University of Tasmania or any other institution. To the best of my knowledge and belief this thesis contains no material previously published or written by another person except where due acknowledgment is made in the text of the thesis.

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Abstract

The optimum age for early selection of eucalypts in breeding to minimise the total cost of producing kraft pulp was investigated.

The effect of future changes in density and pulp yield on the cost of converting roundwood to unbleached kraft pulp was modelled by defining cost functions for each stage of the kraft pulping process. The pulping cost function was combined with cost functions for growing, harvesting, and transporting plantation-grown eucalypt wood to derive a production function for the total cost of kraft pulp production in relation to the biological traits of growth rate, stem form, basic density and pulp yield. The economic value of trait improvement was combined with assumed genetic parameters to determine expected gain towards the objective for a given breeding effort in each trait. Density and growth were shown to be the most important traits for breeding, followed by pulp yield and stem form, with relative values of 3.6, 3.2, 1.9 and 1 respectively. Breeding to improve only density and growth was demonstrated to achieve 95% of the gain possible from breeding for all four traits.

Pith-to-bark density profiles were determined for 588, 7-year-old plantation grown *Eucalyptus nitens* trees. Results were aggregated to derive age-age correlations for density which were shown to be high. Age-age correlations for growth were determined across a greater sample using height measured at 20 months and diameter at 1.3 m measured at four years and seven years. Based upon dual trait selection for density and growth, the optimum economic age for early selection, the selection age where the present value of all future gains is maximised, was determined to be three years. The optimum biological selection age, the selection age where average annual gain is maximised, was determined to be four years.

Assessing wood properties is expensive and time consuming, reducing considerably the use of these traits in selection programs. The thesis demonstrated the application of the Pilodyn in the indirect selection of density in *E. nitens*, with very high genetic correlation (r_g=-0.92) between Pilodyn penetration and density. The application Near Infrared Reflectance Analysis (NIRA) in the indirect selection of pulp yield was explored, however problems with calibration left results inconclusive.

This thesis clearly points to an increasing emphasis on wood properties, in particular wood density, in selection decisions and to a reduction in selection age to as early as three years of age. Such practices are expected to impact significantly on the overall costs of producing eucalypt kraft pulp in Australia.

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Publications from this Thesis

Refereed publications

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Greaves, B.L. and Borralho, N.M.G. 1996. The influence of basic density and pulp yield on the cost of eucalypt kraft pulping: a theoretical model for tree breeding. *Appita Journal* **49**: 90-95.

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Greaves, B.L., Borralho, N.M.G. and Raymond, C.A. 1997. Breeding objective for plantation eucalypts grown for production of kraft pulp. *Forest Science* **43**: (*in press*).

Greaves, B.L., Borralho, N.M.G. and Raymond, C.A. 1997. Assumptions underlying the use of economic weights - are they valid in breeding for eucalypt kraft pulp? *Forest Genetics* **4**: 35-42.

Conference proceedings

Greaves, B.L., Borralho, N.M.G. and Raymond, C.A. 1995. Use of a Pilodyn for the indirect selection of basic density in *Eucalyptus nitens*. *In* CRCTHF - IUFRO Conference. Eucalypt Plantations: Improving Fibre Yield and Quality, Hobart, Australia (*Eds.* Potts, B.M. *et al.*). Co-operative Research Centre for Temperate Hardwood Forestry. pp 106-109.

Greaves, B.L. and Borralho, N.M.G. 1996. The influence of basic density and pulp-yield on the cost of eucalypt kraft pulping: a theoretical model for tree breeding. *In* 50th Appita Annual General Conference & 1996 Pan Pacific Conference, Auckland, NZ. Appita. Vol. 2, pp. 859-864.

Articles currently in review

Greaves, B.L., Borralho, N.M.G., Raymond, C.A., Evans, R. and Whiteman, P. (*in review*) Age-age correlations in, and relationships between basic density and growth in *Eucalyptus nitens*. *Silvae Genetica*

Greaves, B.L., Borralho, N.M.G. and Raymond, C.A. Early selection for kraft pulp in plantation eucalypts. This paper is currently undergoing internal CSIRO review prior to submission to *New Forests*

Table of Contents

The format of presented chapters

Most chapters of this thesis have been or are in the process of being published as scientific papers in international journals. Whilst each chapter retains the structure of the scientific paper as published, the following changes have been made to enhance the flow of this thesis:

- bibliographies have been removed and aggregated to a single bibliography at the end of the thesis;
- abstracts, summaries and general acknowledgments have been removed;
- tables, figures, equations and appendices have been renumbered with the chapter number, e.g. Table 4 in Chapter 3 has been renumbered as Table 3.4;
- cross-references to published scientific papers which are contained as chapters in this thesis have been changed to the relevant chapter reference, e.g. "Greaves and Borralho (1996)" has been changed to "Chapter 2";
- minor changes have been made to the text to support the changes described above and to maintain the general flow; and
- the contributions of other authors to the research presented in each chapter are specifically acknowledged at the end of each chapter as appropriate.

Each chapter of this thesis has been presented such that it stands alone as a report of scientific research. As such, some tables presented in earlier chapters are repeated in subsequent chapters. The repeated tables have been retained in the thesis as they improve the readability and thus the flow of the work as a whole.

Chapter 1:

Introduction

Wood is one of our most important natural resources. Wood is derived from air and water, a few trace elements uptaken from soil, and a considerable amount of stored solar energy. Wood is renewable - it can be grown, it is recyclable, it is biodegradable, and it can be combusted to release the stored solar energy leaving only air and water and a little ash.

Initially, wood was sourced from naturally grown forests, but as demand increased, trees were established as intensively managed plantations. Eucalypts are among the great diversity of tree genera which have been domesticated for commercial utilisation.

Of the 500 or so species of eucalypt, only two occur naturally outside Australia. Yet eucalypts can be grown in most tropical and temperate regions between latitudes 45°S and 40°N, and an estimated total of 6,000,000 hectares of eucalypt plantation (estimates for 1985 after Eldridge *et al.* 1993) have been established for commercial use in over 70 countries.

Plantation eucalypts grown throughout the world are used for timber, reconstituted wood products, fuel, shelter and pulp for paper. In most cases, however, the difficulties of sawing fast grown plantation eucalypts economically (Page 1984) mean intensively managed eucalypt plantations are grown almost exclusively as a source of pulp for paper-making.

As with many other genera, eucalypts have shown considerable between- and within-species variation for traits of commercial importance, and a significant proportion of observed within-species variation has often been shown to be genetic. Breeding programs have been established around the world to exploit genetic variation with the aim of improving the profitability of eucalypt plantation enterprises: to breed trees which grow faster, or which survive better in adverse conditions, or which are better suited to the desired end use in some way.

Quantitative genetics is a discipline which applies statistical theory to the description of genetic variation in populations. It has been widely used in agricultural systems with animals and crop plants and has resulted in considerable improvement. Whilst quantitative genetics has been applied to tree improvement in forestry for some years now, the long generation times and difficulties with controlled fertilisation and propagation have meant progress has been relatively slow.

The first stage in any tree improvement program is the choice of the breeding objective, or in other words, what the breeder seeks to maximise in the population. Incorrect definition of the objective may result in the wrong individuals being chosen for further breeding leading to reduced gains, or in the worst case, a reduced suitability of plantation trees for their end-use. In all cases a more accurate definition of the breeding objective represents an opportunity for the forest grower to increase gains from breeding at no extra cost (Amer 1994). The second stage is the identification of the most appropriate selection criteria to achieve the defined objective, that is, what should be measured and when should it be be measured.

1.1 BREEDING OBJECTIVE

Industrial forest growers in Australia have identified four biological traits as being somehow important to the profitability of eucalypt plantations grown for kraft pulp production:

standing volume at harvest: the green volume of timber which can be harvested from a hectare of forest estate at rotation end - this trait incorporates both growth rate and survival and has the units of cubic metres per hectare;

basic density at harvest: the dry weight of wood per unit of green volume in oven-dry tonnes (ODt) per cubic metre;

pulp yield: the dry weight of kraft pulp produced as a fraction of the total dry weight of wood, in oven-dry tonnes of pulp per oven-dry tonnes of wood; and

stem form: the general form of trees at harvest, incorporating the straightness of stem and degree of branching - this trait is commonly defined as a six

point score where a score of six represents very good form and a score of one represents very poor form.

Little work has been published, however, which defines the relative importance of these traits - that is, how much weight should be given to growth rate over pulp yield or stem form for example, or is a tree with very good stem form better than a tree with high basic density? Early work in tree improvement concentrated on growth and form traits, with little or no consideration given to the impact of gains on the cost of pulping. Yet the cost of pulping is by far the dominant cost in the total cost of producing pulp.

Borralho *et al.* (1993) explored the influence of some of these traits on the kraft pulp production system, but included the pulping cost as simply being inversely related to density and pulp yield. Chapter 2 of this thesis examines in much greater detail the influence of basic density and pulp yield on the cost of converting logs to unbleached pulp by defining cost functions for each stage in the kraft pulping process. Chapter 3 of this thesis draws on the pulp-mill cost functions derived in Chapter 2 and on the work of Borralho *et al.* (1993) and defines a total-cost function for the production of unbleached kraft pulp. The relative importance to breeding of the four traits, growth rate, basic density, pulp yield and stem form, are determined, based upon their respective genetic variation and economic significance to the breeding objective.

Economic information derived from breeding objectives has been classically applied in breeding programs through the use of economic weights (Ponzoni 1986), which are defined as the gain towards the breeding objective (of reducing cost or maximising profit) attributable to a unit change in each trait (e.g. Dean *et al.* 1990). Economic weights are often reported as if they are constant, yet non-linearity of the production function causes the economic weight to change with change in a trait. Chapter 4 of this thesis examines the validity of deriving and using constant economic weights for each trait, in the context of early generation eucalypt breeding and the breeding objective defined in Chapter 3.

1.2 SELECTION SYSTEMS

Having defined the breeding objective, or what the breeder should be improving, the next question is how to assess or predict the traits defined as being important.

Diameter at 1.3 m (*dbh*) has long been accepted as being well correlated with total tree volume (Cotteril and Dean 1990) and thus selection for growth is relatively well defined. Yet direct selection for density in breeding programs requires the removal and analysis of wood samples either in the form of increment cores or disks, work which can be very costly for large numbers of samples and which may result in the death of sampled trees. Chapter 5 examines the application of a Pilodyn in the indirect selection of basic density in breeding programs.

Pulp yield has long been believed to be one of the most important traits of influence on the profitability of kraft pulping enterprises. Currently pulp yield can only be assessed by actually pulping samples of wood in mini-scale laboratory digesters at a cost of around AUD$500 per sample (Phil Whiteman personal communication[1]). Thus, assessment of pulp yield in breeding programs has been severely limited by cost, with assessments being made only at a family level rather than at the individual-tree level. Analysis of near infrared reflectance (NIR) spectra of woodmeals has been shown to have application in the indirect assessment pulp yield (Michell 1995). Chapter 6 examines the genetic control of NIR spectra recorded from 600 *E. nitens* samples, and Chapter 8 evaluates the application of NIR analysis in the indirect selection of pulp yield in breeding programs.

1.3 EARLY AGE SELECTION

The issue of the optimum age to make selections has always challenged tree breeders.

The rotation length of temperate plantation eucalypts in Australia is expected to be 15 to 25 years. If selections for further breeding can be made at an age earlier than rotation age the length of a breeding cycle can be

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[1] Phil Whiteman, Technical Manager, Australian Paper Plantations Pty. Ltd., Morwell, Australia

reduced with the potential to increase the average gain made per year. The accuracy of predicting the best trees, however, declines with decreasing selection age. Chapter 7 examines the age-age correlations of density and growth in *E. nitens*, and Chapter 8 examines the application of NIR analysis in determination of age-age correlations for pulp yield in *E. nitens*.

Currently, the optimum age for early selection in temperate eucalypts is thought to be four years for growth (Borralho *et al.* 1992b) and six years for wood properties such as basic density and pulp yield (Phil Whiteman personal communication). In Chapter 9 the optimum age for early selection towards the breeding objective of reducing the total cost of producing eucalypt kraft pulp is determined.

Chapter 2:

The influence of basic density and pulp yield on the cost of eucalypt kraft pulping: a theoretical model for tree breeding

This chapter has been published as:

Greaves, B.L. and Borralho, N.M.G. 1996. The influence of basic density and pulp yield on the cost of eucalypt kraft pulping: a theoretical model for tree breeding. *Appita Journal* **49**: 90-95.

2.1 INTRODUCTION

Tree breeders tend to ask simple questions of mill managers. For example, if by breeding we increase basic density (density) by 0.05 t m^{-3} or pulp yield by 2% (ODt ODt^{-1}), what difference do these changes make to the cost of pulping? To answer these questions, breeders require a model of processes within the mill as these traits differentially influence the various stages of production. Complex mill models are available (Kerr and Uprichard 1976, Pulp and Paper Research Institute of Canada 1982, Ince 1984, Pu *et al.* 1991), and whilst useful for optimising pulping processes may not directly relate cost to changes in biological traits.

This chapter examines the impact of pulp yield and density on the total cost of converting green roundwood to unbleached kraft pulp by deriving theoretical relationships for each stage of the pulping process, including chipping, digestion and washing, and chemical recovery (evaporators, recovery boiler and recausticizing).

2.2 METHOD

As benefits from the genetic improvement of trees are not expected for 15 to 25 years (the time taken to select, collect, propagate, and grow improved genetic material), the pulp-mill is assumed to be new ("greenfield") where no stage is limiting production, but where the capacity of each stage matches both the required production level and the expected density and pulp yield of the available (genetically improved) plantation wood.

Proportionality statements will be developed for each stage of the pulping process such that the cost per oven-dry tonne of unbleached kraft pulp produced (*COST*) is a function of density (*DENS*) and pulp yield (*PY*):

[2.1] $$COST \propto f(DENS, PY)$$

As we are considering a future greenfield mill, no distinction is made between fixed and variable costs of production as all costs can be considered to be variable in the long-term (Epp and Malone 1981). However, the cost of capital (investment in machinery) is not necessarily linearly related to capacity for large capital items such as the recovery boiler, primarily due to economies of scale. The total cost of each stage can be broken into the cost of capital, and the operating costs (the total of all other costs), with the cost of capital for each stage (*CAPITAL*) being derived from (Wilson 1950):

[2.2] $$CAPITAL \propto f(DENS, PY)^b$$

where b is termed the capital power factor (nominally 0.6 for pulp and paper equipment, after Wilson 1950), and $f(DENS,PY)$ is the function describing the effect of density and pulp yield on the operating cost of each stage of production (Eqn. 2.1).

As the effects of changes in density and pulp yield on pulping costs are being modelled for the purposes of breeding, the increase in each trait is assumed to be independent of change in the other. This may be best understood by considering a planned medium sized mill (say 200,000 tonnes of pulp output annually) with an expected uniform feedstock of plantation eucalypt roundwood having density and pulp yield at given levels (denoted base levels). The feedstock is then changed in single steps: (1) density is increased from a base level of 0.50 t m^{-3} to 0.55 t m^{-3}

without changing pulp yield; and (2) pulp yield is increased from 50% to 52% without changing density. In each case the mill design must be altered accordingly, modifying the relative size of the components to suit the changed wood properties. Thus the influence of density and pulp yield can be modelled by understanding the effect of changes in these traits on the operating and capital costs of each stage in the pulping process of a future mill.

2.2.1 Total cost of pulping

The kraft pulp-mill can be broken into simple stages of production (Figure 2.1). Roundwood is chipped, digested in the presence of Effective Alkali (*EA*) and small quantities of other chemicals, and washed to leave unbleached pulp. The spent cooking liquor (black-liquor), which contains spent *EA* and dissolved organic black-liquor solids (*OBLS*), is concentrated in the evaporators, burnt in the recovery-boiler, and the *EA* recausticized for reuse. Energy liberated in the combustion of *OBLS* is used in the operation of other stages of the pulping process.

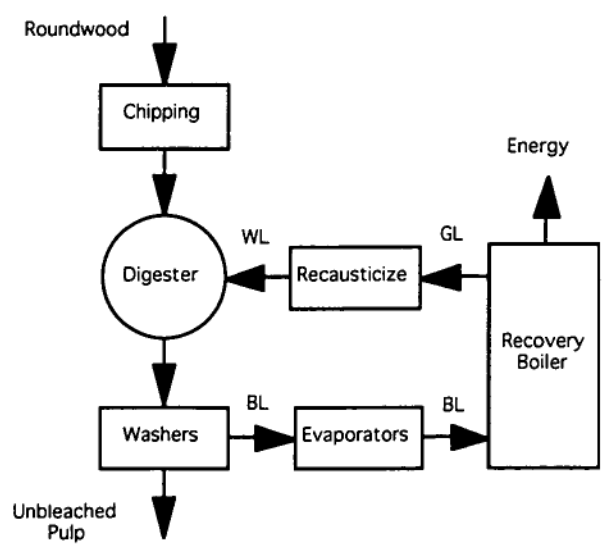

Figure 2.1: A diagrammatic representation of a kraft pulp-mill, where BL is black-liquor, WL is white-liquor, and GL is green-liquor.

The total cost of pulping ($C_{pulping}$) can be derived from:

[2.3] $$C_{pulping} = C_{chip} + C_{dig} + C_{chem} + C_{evap} + C_{rec} + C_{recaust}$$

where C_{chip} is the cost of chipping; C_{dig} is the cost of digestion; C_{chem} is the cost of chemical other than effective alkali consumed during pulping; C_{evap} is the cost of black-liquor evaporation; C_{rec} is the recovery furnace cost; and $C_{recaust}$ is the cost of recausticizing, where all costs are expressed in dollars per oven-dry tonne of unbleached pulp produced. Each of these component costs includes an operating cost and a capital cost: operating costs are directly related to the function of density and pulp yield (Eqn. 2.1) whilst capital costs are related to the function to the capital power (Eqn. 2.2).

Wherever specified in this chapter a tonne of pulp refers to an oven-dry tonne (ODt) of unbleached eucalypt kraft pulp.

2.2.2 *Chipping cost*

Whilst the energy required to chip a given volume of green wood is directly proportional to the density of the wood (McKenzie 1970), the quantity of dry material produced for a given green volume is also directly proportional to density (since basic density is defined as the dry weight per unit of green volume). Lower density wood uses less energy to chip but more wood must be chipped to provide a given quantity of dry matter, and thus the energy cost of chipping per unit of dry material chipped is independent of density.

The quantity of pulp produced per unit of dry matter is determined by pulp yield, so, if chipping cost per unit of dry matter is constant, chipping cost per tonne of pulp produced (C_{chip}) is inversely proportional to pulp yield:

[2.4] $$C_{chip} \propto \frac{1}{PY}$$

2.2.3 Digester cost

The digester is assumed to be a batch digester. The cost of operating the digester includes the cost of energy for heating but does not include the costs of *EA* and other chemicals.

The volume of chips in the digester per batch is assumed to be constant and independent of both density and pulp yield. The energy required to heat the digester is largely constant and also relatively independent of density and pulp yield.

The quantity of white-liquor (*EA* and water) added per digester load is dependent upon the concentration of the white-liquor and the *EA* requirement. The *EA* requirement in turn depends upon the quantity of *OBLS* per digester load for a given furnish - an assumption supported by reported data (Turner *et al.* 1983, Farrington *et al.* 1995). Black-liquor is added to fill the digester and to achieve a liquor-to-wood ratio which will allow adequate circulation during digestion. The costs associated with supply of *EA* for digestion appear as evaporation, recovery-boiler operation and recausticizing costs, and thus the cost of digestion is independent of *EA* requirement. Whilst small quantities of *EA* are lost during washing the cost of replacement is also included in the chemical recovery costs rather than the digester costs.

The digester cost per tonne of pulp produced (C_{dig}) as a function of pulp yield and density is (after Appendix 2.1):

$$[2.5] \quad C_{dig} \propto \frac{1}{PY.DENS}$$

2.2.4 Chemicals other than Effective Alkali used in pulping

Small quantities of chemical are consumed during pulping and washing (for example talc, defoamers, and anthraquinone). The consumption of these chemicals is complex but is most simply approximated by a direct relationship with the dry weight of wood digested (an assumption):

$$[2.6] \quad CHEM \propto DRYWT$$

where *CHEM* is the chemical used per digester load of chips; and *DRYWT* is the dry mass of the green wood in the digester. As the production of

pulp per unit of dry matter is directly proportional to pulp yield, the chemical consumption per tonne of pulp produced (and thus cost of chemical per tonne of pulp produced - C_{chem}) is independent of density and directly but inversely proportional to pulp yield:

$$[2.7] \quad C_{chem} \propto \frac{1}{PY}$$

2.2.5 Evaporator cost

The cost of evaporator operation depends upon the amount of water evaporated per tonne of pulp, and is directly proportional to the difference between the water content of the black-liquor before and after evaporation.

The water contained in the black-liquor before evaporation comprises: (1) the water contribution of the green wood; (2) the water contributed in the white-liquor; and (3) the water added during pulp washing (defined as the *Dilution Factor* - Smook 1992).

Whilst spent black-liquor is added to the digester its water contribution can be ignored since it is associated with a prior digestion event. The black-liquor produced in digestion may be cycled through the digester to retain heat before being concentrated and burnt (Smook 1992).

The water content of the black-liquor leaving the evaporators depends upon the concentration of total black-liquor solids, organic and inorganic, (*BLS*) required for optimal burning in the recovery boiler. The optimal *BLS* concentration is assumed to be independent of density and pulp yield and is approximately 70% (Smook 1992), although the value is determined by the calorific content of the *OBLS* and the equipment design.

Increasing pulp yield increases the pulp produced per digester load thus reducing the evaporation required per tonne of pulp. But increasing pulp yield also reduces the *BLS* per digester load which in turn increases the evaporation required to achieve a constant *BLS* concentration into the recovery boiler.

Increasing density increases the dry weight of wood per digester load, increasing the concentration of *OBLS* in the digester output, which

reduces the evaporation required to achieve a constant *BLS* concentration into the recovery boiler.

It can be shown that the cost of evaporation (C_{evap}) as a function of pulp yield and density can be defined as (after App. 2.2):

$$[2.8] \quad C_{evap} \propto \frac{\frac{1}{DENS} + k_1.(1-PY) - k_2}{PY}$$

where k_1 and k_2 are defined (App. 2.2) in terms of mill and wood parameters which are independent of density and pulp yield, and are approximately 1.6 and 0.7 respectively.

2.2.6 Recovery boiler cost

The cost of recovery boiler operation per tonne of pulp is directly related to the quantity of *OBLS* produced per tonne of pulp (assuming the calorific value of *OBLS* is independent of density and pulp yield). The quantity of *OBLS* per tonne of pulp produced is equal to (after Appendix 2.3):

$$[2.9] \quad OBLS_{tp} = \frac{(1-PY)}{PY}$$

where $OBLS_{tp}$ is the mass of *OBLS* produced per tonne of pulp.

It follows that recovery boiler costs per tonne of pulp produced (C_{rec}) are independent of density, but are directly proportional to one-minus-pulp-yield and inversely proportional to pulp yield:

$$[2.10] \quad C_{rec} \propto \frac{(1-PY)}{PY}$$

It is worth noting that the cost of recovery-boiler operation includes returns from selling energy produced from combustion of *OBLS* and thus the operating cost is negative. The energy is "sold" to other stages of pulp production, mainly the digester and evaporators, and the ability to sell any energy in excess of mill requirements is reflected in the magnitude of the negative recovery-boiler operating cost. A discussion of kraft mills as energy producers is presented by Johnsson (1980).

2.2.7 Recausticizer cost

Assuming that sulphidity is independent of both pulp yield and density, the costs of recausticizing (including lime mud circuit and lime kiln) are directly proportional to the *EA* used per tonne of pulp produced which in turn is directly proportional to the production of *OBLS* per tonne of pulp produced.

Therefore the cost of recausticizing per tonne of pulp produced ($C_{recaust}$) as a function of pulp yield is (App. 2.3):

[2.11] $$C_{recaust} \propto \frac{(1-PY)}{PY}$$

2.3 RESULTS AND DISCUSSION

The cost of each stage of production expressed as a function of pulp yield and density are summarised in Table 2.1.

Table 2.1: The cost of each stage of production as a function of pulp yield (PY) and density ($DENS$). The constants k_1 and k_2 for the evaporator cost are defined in App. 2.2 and are approximately 1.6 and 0.7 respectively.

production stage	cost function - $COST \propto f(DENS, PY)$
chipping	$C_{chip} \propto \frac{1}{PY}$
digester	$C_{dig} \propto \frac{1}{PY.DENS}$
digester chemical (excluding *EA*)	$C_{chem} \propto \frac{1}{PY}$
evaporators	$C_{evap} \propto \frac{\frac{1}{DENS} + k_1.(1-PY) - k_2}{PY}$
recovery	$C_{rec} \propto \frac{(1-PY)}{PY}$
recausticize	$C_{recaust} \propto \frac{(1-PY)}{PY}$

The effect of density and pulp yield on total pulping cost have been examined for three notional pulp-mill cost structures (Table 2.2): (1) a structure where the digester costs are relatively high; (2) a structure where the returns from burning black-liquor solids in the recovery boiler are relatively large; and (3) a structure somewhat intermediate between (1) and (2). In each cost structure the total cost of pulping is $200 ($US) per tonne of pulp produced.

Table 2.2: Three notional pulp-mill cost structures (constructed from greenfield mill costs (Galloway *et al.* 1994) with assistance from John Welsford of Jaakko Pöyry Fluor Daniel, Melbourne): all costs are expressed as US dollars per tonne of oven-dry unbleached pulp produced (numbers in parenthesis are negative).

Cost component	Cost structure		
	high digester costs	high recovery returns	intermediate costs
chipping - operating	$10	$20	$20
chipping - capital	$10	$20	$15
digester - operating	$90	$50	$30
digester - capital	$40	$50	$50
digester chemical - operating	$5	$10	$5
digester chemical - capital	$5	$10	$10
evaporators - operating	$10	$20	$40
evaporators - capital	$10	$20	$15
recovery-boiler - operating	($40)	($80)	($50)
recovery-boiler - capital	$40	$40	$35
recausticize - operating	$10	$20	$15
recausticize - capital	$10	$20	$15
total	$200	$200	$200

Assuming the average pulping cost is $200 per tonne of pulp (Table 2.2), and the average pulp yield and density of the population of trees from which selections are to be made for further breeding are 50% and 0.5 t m^{-3} respectively, the effect on total pulping cost due to deviations in pulp yield and density can be determined. If, for example, an individual tree in the selection population is known to have a pulp yield of 52% and density of 0.55 t m^{-3}, the cost of pulping associated with these improved

traits can be determined by calculating the new operating and capital costs for each stage of production. The recovery-boiler costs under the "high recovery returns" cost structure (Table 2.2) are -$40 per tonne of pulp produced (operating costs -$80 and capital costs $40 per tonne). The recovery-boiler costs are independent of density but decrease with increasing pulp yield (Eqn. 2.10). The new recovery-boiler operating costs can be determined from (where values subscripted *"base"* are the base values):

$$C_{rec(operating)} = C_{rec(operating).base} \cdot \frac{(1-PY)}{PY} \cdot \frac{PY_{base}}{(1-PY_{base})}$$

$$= -\$80 \times \frac{(1-0.52)}{0.52} \times \frac{0.5}{(1-0.5)}$$

$$= -\$74$$

and the new recovery-boiler capital costs can be determined from (combining Eqn.s 2.10 and 2.2):

$$C_{rec(capital)} = C_{rec(capital).base} \cdot \left[\frac{(1-PY)}{PY} \cdot \frac{PY_{base}}{(1-PY_{base})} \right]^{b}$$

$$= \$40 \times \left[\frac{(1-0.52)}{0.52} \times \frac{0.5}{(1-0.5)} \right]^{0.6}$$

$$= \$38$$

The total recovery-boiler cost for wood with pulp yield of 52% is -$36 (-$74 + $38) per tonne of pulp produced - an increase of $4 from the total recovery-boiler cost of -$40 for a base pulp yield of 50%.

The effect of density and pulp yield on the total cost of pulping is depicted in Figure 2.2 and Figure 2.3 respectively for the three cost structures presented in Table 2.2.

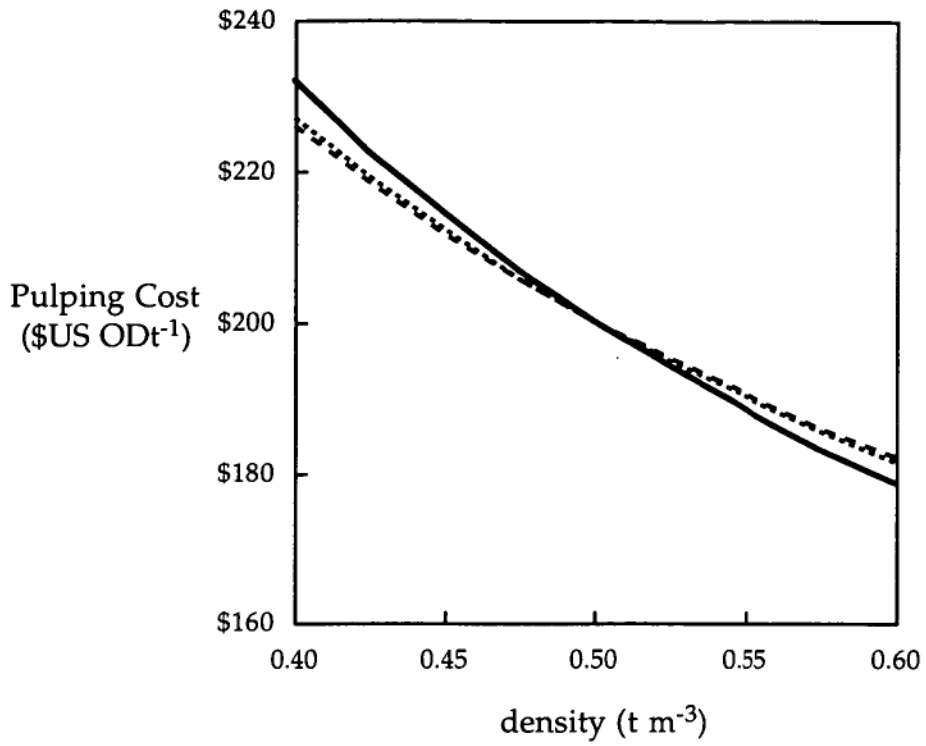

Figure 2.2: Total pulping cost (US dollars per oven-dry tonne of unbleached kraft pulp - US$ ODt^{-1}) versus density, for three pulp-mill cost structures: high digester costs (———); high recovery returns (.....); and intermediate costs (- - - -).

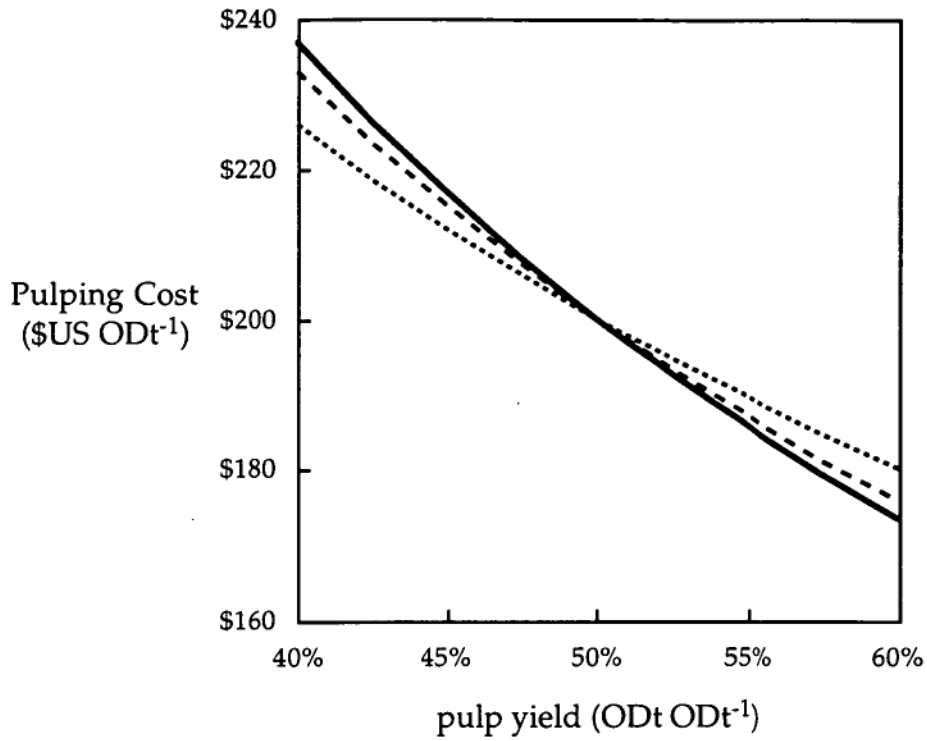

Figure 2.3: Total pulping cost (US dollars per oven-dry tonne of unbleached kraft pulp - US$ ODt^{-1}) versus pulp yield, for three pulp-mill cost structures: high digester costs (———); high recovery returns (.....); and intermediate costs (- - - - -).

The total cost of pulping ($C_{pulping}$) as a function of density and pulp yield as depicted in Figures 2.2 and 2.3 can be approximated by:

$$[2.12] \quad C_{pulping} \propto \frac{1}{(DENS)^{kD}(PY)^{kP}}$$

where kD and kP are dependent upon the base pulping cost structure (Table 2.3).

Table 2.3: The values of kD and kP (Eqn. 2.12), by pulping cost structure (Table 2.2)

cost structure	kD	kP
high digester costs	0.65	0.77
high recovery returns	0.55	0.56
intermediate costs	0.53	0.70

A higher value of *kD* reflects a greater influence of density on the cost of pulping. Density has a major influence on the cost of digestion and a minor influence on the cost of evaporation (Table 2.1), and therefore the value of *kD* reflects primarily the relative contribution of the digester costs to the total cost of pulping (the "high digester cost" structure shows the highest *kD* - Table 2.3).

A higher value of *kP* reflects a less negative recovery boiler operating cost. If the value of energy produced by the recovery-boiler is considerable (leading to a large negative operating cost) increasing pulp yield reduces the negative value (Eqn. 2.10) so increasing the recovery-boiler component of the total cost of pulping. Therefore a high energy value serves to reduce the cost savings of an increase in pulp yield, as demonstrated by the "high recovery return" cost structure having the lowest *kP*.

A previous study (Borralho *et al.* 1993) assumed the cost of pulping to be directly and inversely related to both density and pulp yield (i.e. *kD* and *kP* equal to 1.0). This would have over-estimated the value of improving these traits in breeding programs.

It cannot be concluded however that pulp yield is a more important trait than density in breeding for kraft pulp. Whilst the cost of converting roundwood to unbleached pulp is a major component of the total cost of producing pulp, the cost of growing, harvesting, and transporting roundwood is considerable, and the effect of pulp yield and density on these costs must be considered. Further, the emphasis given to improvement of a trait in a breeding program is dependent upon the degree of inherent genetic variation of that trait, and whilst pulp yield shows a greater influence on the cost of pulping than density, density shows a greater degree of exploitable genetic variation than pulp yield (e.g. Dean *et al.* 1990).

2.4 CONCLUSION

For a new mill, the cost of converting green roundwood to unbleached pulp, expressed in dollars per oven-dry tonne of unbleached pulp, will decrease with increasing density and pulp yield.

Pulp-yield has the greatest effect on pulping cost, but the degree of influence depends upon the value of energy produced by the recovery boiler: a high energy value reduces the influence of pulp yield on pulping cost.

Density has a major influence on the cost of digestion and a minor influence on the cost of evaporation, so a high relative digestion cost increases the influence of density on pulping cost. Pulping cost ($C_{pulping}$) as a function of density ($DENS$) and pulp yield (PY) can be approximated by:

$$C_{pulping} \propto \frac{1}{(DENS)^{kD}(PY)^{kP}}$$

where kD and kP are approximately 0.5 and 0.7 respectively although these values are dependent upon the relative cost structure of the pulp-mill.

APPENDIX 2.1 - Cost of digestion

The digester cost (C_{dig}) can be derived from the cost per batch (C_{batch}) and the quantity of pulp produced ($PULP$):

[A2.1-1] $$C_{dig} = \frac{C_{batch}}{PULP}$$

Further:

[A2.1-2] $$PULP = GVOL.DENS.PY$$

where $GVOL$, $DENS$, and PY are the green volume, density and pulp yield of chips in the digester respectively.

Substituting [A2.1-2] for $PULP$ in [A2.1-1]:

[A2.1-3] $$C_{dig} = \frac{C_{batch}}{GVOL.DENS.PY}$$

As C_{batch} and $GVOL$ are considered to be constant, equation [A2.1-3] resolves to:

[A2.1-4] $$C_{dig} \propto \frac{1}{DENS.PY}$$

APPENDIX 2.2 - Cost of evaporation

The cost of evaporation (C_{evap}) per tonne of pulp produced is assumed to be directly proportional to the water evaporated (W_e) per tonne of pulp produced:

[A2.2-1] $$C_{evap} \propto W_e$$

The water evaporated per tonne of pulp produced is equal to the water going into the evaporators (W_{in}) minus the water coming out of the evaporators (W_{out}):

[A2.2-2] $$W_e = W_{in} - W_{out}$$

The water going into the evaporators comprises the water contribution of the green wood (W_{wood}), the water contribution of the white-liquor (W_{wl}) and the water added during washing (the *Dilution Factor - DF*):

[A2.2-3] $$W_{in} = W_{wood} + W_{wl} + DF$$

The water contained in the wood per tonne of pulp produced (W_{wood}) can be derived from density (*DENS*) and pulp yield (*PY*). Firstly, the mass of water in the wood is equal to the volume of water in the wood (assuming the specific gravity of water is one), which is equal to the difference between the green volume of the wood (*GVOL*) and the total volume of the cell-wall material (*DVOL*):

[A2.2-4] $$W_{wood} = \frac{(GVOL - DVOL)}{PULP}$$

where *PULP* is the total pulp produced. Since:

[A2.2-5] $$DVOL = \frac{DRYWT}{SGW}$$

where *DRYWT* is dry weight, and *SGW* is the specific gravity of the cell-wall material (nominally 1.5 t m^{-3} - Kellogg *et al.* 1975). Substituting [A2.2-5] for *DVOL* in [A2.2-4]:

[A2.2-6] $$W_{wood} = \frac{GVOL}{PULP} - \frac{DRYWT}{SGW.PULP}$$

Since: ,

[A2.2-7] $$\frac{GVOL}{PULP} = \frac{GVOL}{DRYWT} . \frac{DRYWT}{PULP} = \frac{1}{DENS} . \frac{1}{PY}$$

then substituting [A2.2-7] into [A2.2-6]:

[A2.2-8] $$W_{wood} = \frac{1}{DENS.PY} - \frac{1}{SGW.PY}$$

The water contributed by the white-liquor (W_{wl}) can be determined from the *EA*-to-*OBLS* ratio (*EA:OBLS*, in tonnes of *EA* per tonne of *OBLS* in the digester) and the white-liquor concentration ([*WL*], in tonnes of *EA* per cubic metre of water):

[A2.2-9] $$W_{wl} = \frac{(EA:OBLS)}{[WL]} . \frac{OBLS}{PULP}$$

Substituting [A2.3-5] (Appendix 2.3) into [A2.2-9]:

[A2.2-10] $$W_{wl} = \frac{(EA:OBLS)}{[WL]} . \frac{(1-PY)}{PY}$$

The quantity of water added during pulp washing over and above the water which displaces the black-liquor from the pulp is defined as the *Dilution Factor* which is the extra evaporation load per tonne of pulp (Smook 1992). Whilst *Dilution Factor* is often considered to be relatively constant, it is more likely that a constant residual concentration of *OBLS* is required in the pulp after washing. An increase in pulp yield will reduce the *OBLS* content per unit of pulp produced, reducing the washing required to achieve the desired *OBLS* concentration. Thus the *Dilution Factor* (*DF*) is proportional to the concentration of *OBLS* per tonne of pulp (Appendix 2.3):

[A2.2-11] $$DF \propto \frac{(1-PY)}{PY}$$

Converting [A2.2-11] to an equality relationship:

[A2.2-12] $$DF = k . \frac{(1-PY)}{PY}$$

where k is a constant. Rearranging [A2.2-12] for k:

[A2.2-13] $$k = DF . \frac{PY}{(1-PY)}$$

Thus:

[A2.2-14] $$DF.\frac{PY}{(1-PY)} = k = DF_b.\frac{PY_b}{(1-PY_b)}$$

where "*b*" subscripted values are base (initial) values. Rearranging [A2.2-14] for *DF*:

[A2.2-15] $$DF = DF_b.\frac{PY_b}{(1-PY_b)}.\frac{(1-PY)}{PY}$$

where *DF* is the *Dilution Factor* (tonnes of water per tonne of pulp); *PY* is pulp yield; and "*b*" subscripted terms are base values. The base *Dilution Factor* (DF_b) is around 1.5 t_{water} per t_{pulp} and is a function of the type of washing process employed (Smook 1992).

The amount of water going from the evaporators into the recovery-boiler per tonne of pulp produced may be determined from the concentration of total black-liquor solids. Firstly, the concentration of total black-liquor solids into the recovery-boiler ([*BLS*]) is:

[A2.2-16] $$[BLS] = \frac{BLS}{BLS + W}$$

where *W* is the total water into the recovery boiler; and *BLS* is the total black-liquor solids. Rearranging [A2.2-16] for *W*:

$$W = \frac{BLS}{[BLS]} - BLS$$

which reduces to:

[A2.2-17] $$W = BLS.\left(\frac{1}{[BLS]} - 1\right)$$

Secondly, the total mass of black-liquor solids (*BLS*) is equal to the total of the masses of organic black-liquor solids (*OBLS*) and spent *EA*. Since the mass of spent *EA* is assumed to be equal to the mass of *EA* consumed in digestion, and since *EA* is equal to the mass of *OBLS* multiplied by the *EA*-to-*OBLS* ratio for digestion (*EA:OBLS*) then:

$$BLS = OBLS + OBLS.(EA{:}OBLS)$$

which reduces to

[A2.2-18] $$BLS = OBLS.(1+(EA{:}OBLS))$$

The water contained in the black-liquor out of the evaporators per tonne of pulp (W_{out}) is:

[A2.2-19] $$W_{out} = \frac{W}{PULP}$$

where *PULP* is the total pulp produced. Substituting [A2.2-17] for *W* in [A2.2-19]:

[A2.2-20] $$W_{out} = \frac{BLS}{PULP}.\left(\frac{1}{[BLS]}-1\right)$$

Substituting [A2.2-18] for *BLS* in [A2.2-20]:

$$W_{out} = \frac{OBLS.(1+(EA{:}OBLS))}{PULP}.\left(\frac{1}{[BLS]}-1\right)$$

and since $\frac{OBLS}{PULP} = \frac{(1-PY)}{PY}$

[A2.2-21] $$W_{out} = \frac{(1-PY)}{PY}.(1+(EA{:}OBLS)).\left(\frac{1}{[BLS]}-1\right)$$

Substituting equations [A2.2-8], [A2.2-10], [A2.2-15], and [A2.2-21] for (W_{wood}), (W_{wl}), (*DF*), and (W_{out}) respectively into [A2.2-3] and then [A2.2-2] for (W_e):

$$W_e = \left[\frac{1}{DENS.PY} - \frac{1}{SGW.PY}\right] + \left[\frac{(EA{:}OBLS)}{[WL]}.\frac{(1-PY)}{PY}\right]$$

$$+\left[DF_b.\frac{(1-PY)}{PY}.\frac{PY_b}{(1-PY_b)}\right] - \left[\frac{(1-PY)}{PY}.(1+(EA{:}OBLS)).\left(\frac{1}{[BLS]}-1\right)\right]$$

which can be reduced to:

[A2.2-22] $$W_e = \frac{\frac{1}{DENS} + k_1(1-PY) - k_2}{PY}$$

where:

[A2.2-23] $$k_1 = \left[\frac{(EA{:}OBLS)}{[WL]} + DF_b \cdot \frac{PY_b}{(1-PY_b)} - (1+(EA{:}OBLS)).\left(\frac{1}{[BLS]} - 1\right)\right]$$

and

[A2.2-24] $$k_2 = \frac{1}{SGW}$$

where *DENS* is density; *SGW* is the specific gravity of the cell-wall material; *PY* is pulp yield; (*EA:OBLS*) is the ratio of *EA* to undissolved organic black-liquor solids in the digester; [*WL*] is the concentration of the white-liquor (tonnes of caustic per cubic metre of water); DF_b is the base (initial) *Dilution Factor* of the evaporators (at the base values of pulp yield and density, PY_b and $DENS_b$ respectively); and [*BLS*] is the concentration of black-liquor solids into the recovery boiler. k_1 and k_2 can be approximated as 1.6 and 0.7 respectively.

Since the cost of evaporation per tonne of pulp produced (C_{evap}) is directly proportional to water evaporated by the evaporators per tonne of pulp produced:

[A2.2-21] $$C_{evap} \propto \frac{\frac{1}{DENS} + k_1.(1-PY) - k_2}{PY}$$

APPENDIX 2.3 - Production of Organic Black Liquor Solids per tonne of pulp

The total organic black-liquor solids (*OBLS*) can be calculated from the total dry weight of the wood digested (*DRYWT*) and pulp yield (*PY*):

[A2.3-1] $$OBLS = DRYWT \times (1 - PY)$$

and similarly the total quantity of pulp produced (*PULP*) can be calculated:

[A2.3-2] $$PULP = DRYWT \times PY$$

Rearranging [A2.3-2] for *DRYWT*:

[A2.3-3] $$DRYWT = \frac{PULP}{PY}$$

Substituting [A2.3-3] for *DRYWT* in [A2.3-1]:

[A2.3-4] $$OBLS = \frac{PULP}{PY} \times (1 - PY)$$

The *OBLS* per tonne of pulp produced ($OBLS_{tp}$) is obtained by dividing [A2.3-4] by *PULP*:

[A2.3-5] $$OBLS_{tp} = \frac{OBLS}{PULP} = \frac{(1 - PY)}{PY}$$

Chapter 3:

Breeding objective for plantation eucalypts grown for production of kraft pulp

This chapter has been accepted for publication by *Forest Science* and is currently in press:

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3.1 INTRODUCTION

A central decision in any tree improvement program is the choice of the breeding objective, or in other words, what the breeder seeks to maximise in the population. Incorrect definition of the objective may result in the wrong individuals being chosen for further breeding leading to reduced gains, or in the worst case, a reduced suitability of plantation trees for their end-use. In all cases a more accurate definition of the breeding objective represents an opportunity for the forest grower to increase gains from breeding at no extra cost (Amer 1994).

Eucalypt plantations around the world are predominantly grown as a source of fibre for pulp and paper production, with several breeding programs currently underway to improve plantation productivity. Unfortunately, whilst forest and pulp-mill managers might be prepared to specify the direction that "improvement" in a trait should take and perhaps an optimum level for some traits, little is known about the effect that changes in a trait have upon overall profitability.

Production functions can be used to describe the economic relationship between biological traits, as factors of production in the case of a breeding objective, and final output (profit). The derivation of a breeding objective

based upon production (profit) functions was initially described by Ponzoni (1986) and discussed by Amer and Fox (1992). Dean *et al.* (1990) and Fonseca *et al.* (1995) utilised simple production functions to examine the influence of growth rate, density and pulp yield on the profitability of specific eucalypt kraft pulp mills. However, these studies assumed capital costs in the pulp-mill production system to be fixed and hence the apparent value of each biological trait represented not only its value in reducing costs but also its value in overcoming existing production bottlenecks.

In temperate forestry, however, it will be at least 20 years before breeding decisions made today have an effect on mill costs, by which time existing pulp-mills may have been largely rebuilt and more optimally designed to accommodate the changes in wood properties introduced by genetic improvement. Since all costs become variable in the long-term (Epp and Malone 1981), the economic importance of biological traits should be evaluated assuming that both capital and operating costs are variable.

The objective of any enterprise is the maximisation of profit, where profit is defined in terms of selling price, production cost and production quantity. However, growing trees for kraft pulp is a long-term venture and prediction of production level and selling price at least 20 years into the future is difficult. Further, economic theory dictates that a future high selling price should not be assumed: a high margin between price and cost attracts new producers into the market, increasing supply and reducing both selling price and margin (Samuelson *et al.* 1970). As margins are eroded and selling price approaches production cost, the production functions for maximising profit and minimising cost converge. Reducing production cost will always increase profit, and for long-term ventures such as forestry, minimising cost seems a sensible objective.

This chapter will describe the kraft pulp production system, from growing trees to the production of unbleached kraft pulp. A production function, largely derived from previously published material (Chapter 2, Borralho *et al.* 1993), will be used as a basis for determining economic weights for standing volume at harvest, density, pulp yield, and stem form. The objective for breeding is the reduction of the total production cost of unbleached kraft pulp, where both capital and operating costs are assumed to be variable. The relative importance of each trait for breeding will be examined using simulated data.

3.2 METHODS

3.2.1 Traits in the objective

Standing volume (*VOL*) is defined as the merchantable volume per hectare at harvest (m^3 ha^{-1}). It is an aggregate of both growth and survival traits (assuming constant rotation length for all genotypes). Basic density (*DENS*) is the oven-dry weight of wood per unit green volume (ODt m^{-3})[#1]. Pulp yield (*PY*) is the oven-dry weight of pulp per unit oven-dry weight of wood (ODt ODt^{-1}), and is assumed to be the true digester pulp yield. In this study stem form (*FORM*) is included as a six-point score representing both stem straightness and branch size (e.g. Cotterill and Dean 1990) - a higher score is associated with better general form.

These traits are all defined as breeding objective traits, that is, they are characteristics of the plantation at harvest age which the breeder wishes to improve. The indirect selection of these traits, for example the measurement of *dbh* on an individual tree to predict *VOL*, or Pilodyn penetration for *DENS*, will depend upon the genetic relationships between the selection traits and the breeding objective traits. The definition of appropriate selection criteria will be further discussed in Chapters 5 - 8.

3.2.2 The cost function

The main elements of the cost of producing unbleached kraft pulp from plantations are (1) the costs associated with growing plantations; (2) the costs of harvesting the grown trees and transporting the roundwood to a pulpmill; and (3) the cost of converting roundwood to unbleached kraft pulp.

3.2.2.1 Growing cost of plantation pulpwood

The cost of growing plantation eucalypts includes the cost of land use, the cost of plantation establishment, and the cost of maintenance over the life of the plantation.

[#1] "t" denotes metric tonne = 1,000 kg = 1.103 US ton

Whilst it may be reasonable to assume that, in the longer term, there will be no cost of owning land which is appreciating in value (e.g. Borralho *et al.* 1993), in this analysis the cost of land-use has been included as an annual charge simulating rental or interest on invested capital. The cost of land-use should also include any other annual land-use costs such as property tax.

The cost of plantation establishment includes the costs of: preparation of the site such as cultivation and weed control; growing seedlings in a nursery; planting; and any necessary fertilising at planting. Plantation maintenance includes the cost of fire prevention, weed control and fertilisation (as required) and any other activities which occur during the life of the plantation. Maintenance has been approximated by an annual area-based charge.

As the costs of land, plantation establishment and plantation maintenance are all land-area based costs, each can be reduced to a cost per tonne of pulp produced (C_{land}, C_{est} and C_{main} respectively) by dividing by *VOL*, *DENS*, and *PY* (after Borralho *et al.* 1993). Thus:

$$[3.1] \quad C_{land}, C_{est} \text{ and } C_{main} \propto \frac{1}{VOL.DENS.PY}$$

3.2.2.2 *Harvesting and transport costs*

Harvesting of pulp-wood involves felling of trees, removal of logs to a landing in the forest, debarking and loading of roundwood onto a truck for transport. Harvesting is often costed on the basis of cubic metres or equivalent green tonnes of wood harvested.

Increasing either *DENS* or *PY* increases the tonnes of pulp harvested per cubic metre, and thus the cost of harvesting per tonne of pulp (C_{harv}) will decrease with an increase in either trait (Borralho *et al.* 1993). Tree size has some effect on C_{harv} with small logs tending to be more costly to harvest per cubic metre than large logs and thus *VOL* has some influence on harvesting costs (under constant stocking density). In addition, trees of poor *FORM* cost more to harvest per cubic metre than trees of good form. Using unpublished data relating tree size and form with harvesting cost (after Australian Paper Plantations Pty. Ltd., Australia), and the relationship for harvesting cost presented by Borralho *et al.* (1993), the following approximate relationship was developed:

$$[3.2] \quad C_{harv} \propto \frac{1}{VOL^{0.2}.DENS.PY.FORM^{0.1}}$$

Transport of roundwood is largely by road with trucks limited in the weight of logs they can carry. As a full weight load is usually well within maximum volume restrictions log form (shape) has little effect on the transport cost of roundwood. Transport cost is also independent of standing volume at harvest. Borralho *et al.* (1993) demonstrated that increasing either *DENS* or *PY* will reduce the cost of transport per tonne of pulp (C_{trans}):

$$[3.3] \quad C_{trans} \propto \frac{1}{DENS.PY}$$

3.2.2.3 Costs of converting roundwood to pulp (pulping)

Roundwood delivered to the pulpmill is chipped. A fixed volume of chips is digested in the presence of "*caustic*" (*Effective Alkali* or *white-liquor*) and small quantities of other chemicals. The digester is heated and pressurised using steam to around 180°C and 10 atmospheres. The lignin holding the wood together is largely dissolved, along with some hemicellulose, leaving pulp which is predominantly cellulose. The pulp is screened and washed for paper manufacture. The digested lignin and hemicellulose exits the digester with the spent caustic as *black-liquor* passing through evaporators to drive off excess water before being burnt in the recovery furnace. The combustion of lignin and hemicellulose liberates energy which is used in the operation of other stages of the pulping process with excess being "sold" to paper manufacture or to domestic power grids. Recovered chemical from the recovery furnace is converted in the caustic recovery stage to white-liquor for reuse in the digester.

The cost of pulping is independent of *VOL*. Whilst *FORM* has some effect on the cost of chipping the effect is small and has been ignored.

The influence of *VOL*, *FORM*, *DENS*, and *PY* on each component of total pulp-cost are summarised in Table 3.1.

Table 3.1: The cost of each stage of production, in US dollars per oven-dry tonne of unbleached eucalypt kraft pulp i.e. $ per ODt UBEK, as a function of standing volume at harvest (*VOL*), stem form (*FORM*), pulp yield (*PY*) and density (*DENS*). Costs of pulping stages (after Chapter 2) are split into total operating cost and capital cost (*operating/capital*), and numbers in parenthesis are negative.

production stage	cost function - $COST \propto f(VOL, DENS, PY, FORM)$	base cost ($US per ODt UBEK)	timing of cost
cost of land	$C_{land} \propto \frac{1}{VOL.PY.DENS}$	1.6	annual cost
plantation establishment	$C_{est} \propto \frac{1}{VOL.PY.DENS}$	24	rotation start
plantation maintenance	$C_{main} \propto \frac{1}{VOL.PY.DENS}$	1.6	annual cost
harvesting	$C_{harv} \propto \frac{1}{VOL^{0.2}.FORM^{0.1}.PY.DENS}$	80	rotation end
transport	$C_{trans} \propto \frac{1}{PY.DENS}$	40	rotation end
chipping	$C_{chip} \propto \frac{1}{PY}$	20/15	rotation end
digester	$C_{dig} \propto \frac{1}{PY.DENS}$	30/50	rotation end
chemical (excluding EA)	$C_{chem} \propto \frac{1}{PY}$	5/10	rotation end
evaporators	$C_{evap} \propto \frac{\frac{1}{DENS} + 1.6(1-PY) - 0.7}{PY}$	40/15	rotation end
recovery	$C_{rec} \propto \frac{(1-PY)}{PY}$	(50)/35	rotation end
recausticize	$C_{recaust} \propto \frac{(1-PY)}{PY}$	15/15	rotation end

Discounting has been employed to accommodate time differences in the occurrence of costs (Table 3.1) . A discount rate of 5% has been used in this analysis, however published discussion regarding the choice of discount rate has been considerable (see Price 1973 and Klemperer *et al.* 1994). The

rotation length, the time between plantation establishment and harvest, has been assumed to be 15 years.

The total pulp-cost (C_{total}), expressed in dollars, per oven-dry tonne of unbleached pulp, discounted to the time of plantation establishment is:

$$C_{total} = \frac{[C_{est}]}{(1-loss)} + \frac{[C_{main} + C_{land}]}{(1-loss)} \cdot \left[\frac{1-(1+d)^{-r}}{d}\right] + \frac{[C_{harv} + C_{trans}]}{(1-loss).(1+d)^{r}}$$

[3.4]

$$+ \frac{\left[C_{chip} + C_{dig} + C_{chem} + C_{evap} + C_{rec} + C_{recaust}\right]}{(1+d)^{r}}$$

where C_{est} is the cost of plantation establishment; C_{main} is the annual maintenance cost; C_{land} is the annual cost of land; C_{harv} is the cost of harvesting; C_{trans} is the cost of transport; *loss* is the fibre loss in the pulpmill expressed as a fraction of total delivered fibre, assumed to be 5%; r is the rotation length; $d$is the discount rate; C_{chip} is the cost of chipping; C_{dig} is the cost of digestion; C_{chem} is the cost of chemical other than effective alkali consumed during pulping; C_{evap} is the cost of black-liquor evaporation; C_{rec} is the recovery furnace cost; and $C_{recaust}$ is the cost of recausticizing. All costs are expressed in US dollars per oven-dry tonne of unbleached pulp produced (Table 3.1).

As benefits from genetic improvement of trees are not expected for at least 15 to 25 years, there is no distinction between fixed and variable production costs as all costs become variable in the long-term (Epp and Malone 1981). However, the cost of capital invested in machinery is not linearly related to capacity for large pulp-mill components, and the relationship between capital cost (*COST*) and capacity (*CAPACITY*) can be shown to be (first described by Wilson 1950):

[3.5] $COST \propto (CAPACITY)^{0.6}$

3.2.3 Economic weights

Economic weights, defined as the change in the objective (savings in total pulp cost) associated with a unit increase in a trait, were calculated over an increase in each trait of 0.1 additive standard deviations (σ_a - Table 3.2), calculated at the population mean. The presented economic weights, in savings in total pulp cost per *unit increase* in each trait, were calculated as the

observed change in total pulp cost for an increase of 0.1 σ_a divided by 0.1 σ_a for each trait.

3.2.4 Data-set

To examine the influence of individual selection for each trait and multitrait selection on the expected gain towards the breeding objective, fifty 5000 record data-sets were simulated using the Monte-Carlo method. Breeding-values and residual deviations of the four traits in the breeding objective were randomly generated assuming the phenotypic and genetic parameters listed in Table 3.2. The expected gains due to selection were taken as the mean of results of selection applied to each data-set individually.

Table 3.2: Means, additive and phenotypic standard deviations (σ_a, σ_p), heritabilities (diagonal), and genetic (upper diagonal) and phenotypic (lower diagonal) correlations used in generation of the simulated data. Parameters were based upon Dean *et al.* (1990), Chapter 5, and Australian Paper Plantations Pty. Ltd. unpublished data and are typical of early generation *E. globulus* or *E. nitens* populations. Environmental covariances were assumed to be zero.

	unit	mean	σ_a	σ_p	*VOL*	*DENS*	*PY*	*FORM*
VOL	$m^3\ ha^{-1}$	250	38	70	0.30	0.1	0.1	0.4
DENS	$t\ m^{-3}$	0.5	0.022	0.03	0.04	0.55	0.3	0
PY	$ODt\ ODt^{-1}$	0.5	0.0077	0.013	0.03	0.13	0.35	0
FORM	score 1...6	3.5	0.36	0.8	0.10	0	0	0.20

3.2.5 Index selection

To compare multitrait selection strategies, coefficients for Smith-Hazel selection indices (e.g. Cotterill and Dean 1990) were calculated after:

[3.6] $\mathbf{b} = \mathbf{P}^{-1}\mathbf{A}\mathbf{w}$

where **b** is a vector of index coefficients; **P** and **A** are the phenotypic and additive variance-covariance matrices respectively (derived from the parameters listed in Table 3.2, where $cov_{a,b} = r\sigma_a\sigma_b$); and **w** is a vector of economic weights.

3.3 RESULTS AND DISCUSSION

3.3.1 Economic weights

For the expected mean values for each trait (Table 3.2) and the assumed component costs (Table 3.1), an increase in *VOL* of one m^3 ha^{-1} resulted in savings of \$0.269 per oven-dry tonne of unbleached eucalypt kraft pulp produced. The equivalent values for increases of *DENS*, *PY*, and *FORM* were \$349 t^{-1} m^3, \$411 t_p^{-1} t_w, and \$1.15 $(\text{score point})^{-1}$ respectively.

The appropriate breeding objective is then given as:

$$[3.7] \quad G = 0.269(VOL_a) + 349(DENS_a) + 411(PY_a) + 1.15(FORM_a)$$

where *G* is the gain towards the objective discounted to the time of plantation establishment and VOL_a, $DENS_a$, PY_a and $FORM_a$ are the genetic values of *VOL*, *DENS*, *PY* and *FORM* at harvest expressed as deviations from the respective population means (see Table 3.2 for means).

Whilst the breeding objective (Eqn. 3.7) describes gain in terms of the genetic worth of each trait, gain can also be expressed in terms of the phenotypic values of each objective trait using the index selection coefficients (vector **b**, after Eqn. 3.6):

$$[3.8] \quad G = 0.0841(VOL_p) + 221(DENS_p) + 214(PY_p) + 1.81(FORM_p)$$

Where VOL_p, $DENS_p$, PY_p and $FORM_p$ are the phenotypic values of *VOL*, *DENS*, *PY* and *FORM* at harvest expressed as deviations from the respective population means.

3.3.2 Value to breeding

The economic weights and index selection coefficients do not, however, allow for an easy interpretation of the importance of a trait to breeding. Firstly, the economic weight for density is \$349 but this represents an increase in density of one ODt m^{-3} from (say) 0.5 to 1.5 ODt m^{-3}, whereas the realistic range of density in *E. globulus*, for example, is 0.4 to 0.6 ODt m^{-3}. Secondly, the degree of exploitable genetic variation (σ_a) and the accuracy of predicting the genotypic value (the square-root of heritability, *h*, in the case of phenotypic selection) differ amongst traits.

It can be shown (Appendix 3.1) that the gain towards the objective for a given selection pressure applied to a single trait (G_t) can be defined in terms of the additive covariances between that trait and the other traits in the objective (vector $\mathbf{a}_{a.t}$), its phenotypic variance ($\sigma_{p.t}$), and the economic weights of all traits in the objective (vector **w**) (after Eqn. A3.1-3, Appendix 3.1):

$$[3.9] \quad G_t \propto \frac{\mathbf{a}_{a.t}\mathbf{w}}{\sigma_{p.t}}$$

When traits in the objective are independent Eqn. 3.9 reduces to $w_t h_t \sigma_{a.t}$, (where w_t is the economic weight for the trait) - the well-known expression for gain from single-trait phenotypic selection (Falconer 1989). The relative value of a given trait for breeding can then be described as the relative gain towards the objective (G_t) for any given selection intensity applied to that trait (Table 3.3).

Table 3.3: The relative value of *VOL*, *DENS*, *PY*, and *FORM* to breeding. Relative values are calculated by dividing $\mathbf{a}_{a.t}\mathbf{w}/\sigma_{p.t}$ for each trait by $\mathbf{a}_{a.t}\mathbf{w}/\sigma_{p.t}$ for *FORM* (being the lowest).

trait	$\mathbf{a}_{a.t}\mathbf{w}/\sigma_{p.t}$	relative value for breeding
VOL	6.39	3.2
DENS	7.24	3.6
PY	3.84	1.9
FORM	2.03	1

It is apparent from Table 3.3 that for single-trait phenotypic selection *DENS* will yield 1.9 times the saving in total pulp-cost as selection for *PY*, and 3.6 times the savings due to selection for *FORM* for any given selection intensity. Selection for *VOL* alone will provide 90% of the gain possible from selection for *DENS*, and 1.7 times the gain possible from selection for *PY* alone.

The expected gains in the objective, calculated directly from the simulated breeding values using Equation 3.7, are depicted in Figure 3.1 for a range of selection intensities, for the multitrait selection index (Eqn. 3.8) and for selection for each trait individually. As indicated by the relative value of the four traits to breeding (Table 3.3), single trait selection for either *DENS* or

VOL provided the greatest gain towards the objective, followed by *PY*, and *FORM*. Selection of any trait individually provides a positive gain as the between-trait correlations are all greater than or equal to zero (Table 3.2).

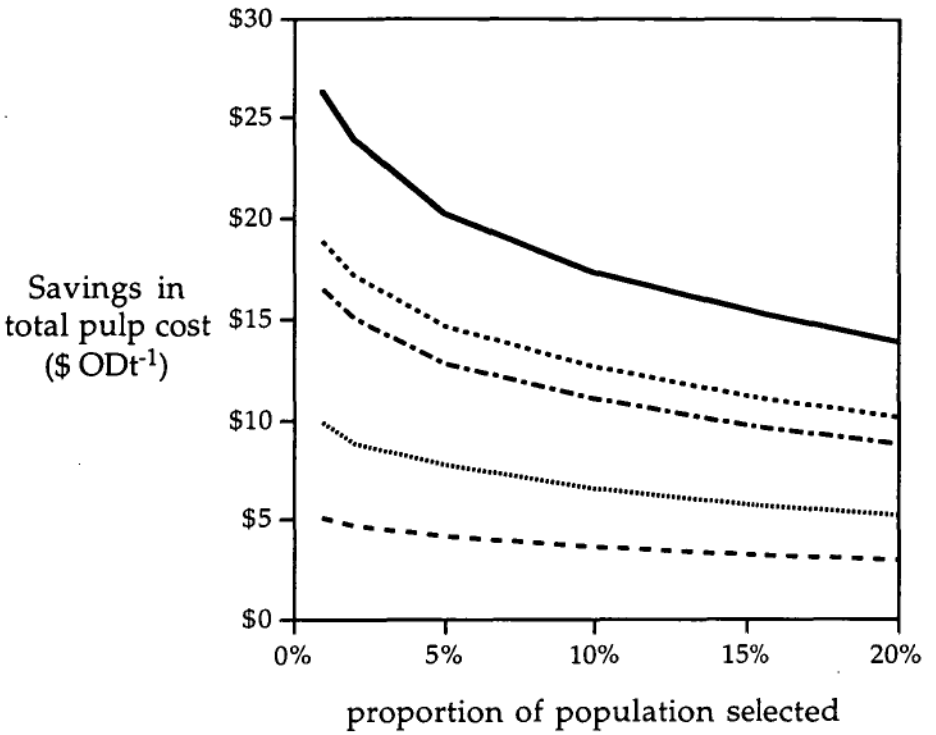

Figure 3.1: Savings in total pulp cost due to selection (discounted to the time of plantation establishment) versus proportion of the population selected, for multi-trait selection (——); and single-trait selection on: density (.....); standing volume (-.-.-); pulp yield (.....); and stem form (- - - -). The presented responses are the simple mean of the observed responses to selection individually applied to 50 simulated data-sets.

If the best 10% of all trees are selected for retention as a seedling seed-orchard on the basis of the multitrait index (Eqn. 3.8), the expected saving in total pulp-cost (Figure 3.2) would be around $17.3 per oven-dry tonne (ODt) of pulp. This is the saving discounted to the time of plantation establishment - the saving at the end of the rotation would be around $36 per ODt, a 10% reduction in cost at current pulp prices. This represents a discounted annual saving of $8.75m, or around $18m at the time of pulping, for a 500,000 tonne-per-year pulpmill. Selection on the basis of *VOL* alone, a common situation in breeding programs, would yield a saving of around $12.6 per ODt, or 68% of the gain possible from dual-trait selection for *VOL* and *DENS*, and 64% of gain possible using all traits in the objective (Eqn. 3.8). Selection on the basis of *PY* alone would save around $6.5 per ODt. Combined selection on the

basis of *VOL* and *DENS*, as described for example by Bridgwater *et al.* (1983) and Borralho *et al.* (1992c), would yield a saving of $16.7 per ODt, or 95% of the gain possible using all traits in the objective.

Previous studies by Dean *et al.* (1990) and Fonseca *et al.* (1995) reported pulp yield as the trait with the greatest effect on pulp-cost. Both these studies considered specific kraft pulp-mills with production bottle-necks in the chemical recovery stages. Under such a scenario, increasing pulp yield increases the pulp which can be produced for a given chemical recovery demand, thus overcoming the pulp-mill bottle-neck. Also, if a high margin between selling price and cost of production is assumed, increasing pulp yield may considerably increase profit and thus the value in improving pulp yield may appear to be high. However, whilst shorter-term deployment decisions may be best made in respect of existing pulp-mill hardware, longer-term decisions should reflect future, more-optimally-designed pulp-mills. In addition, the attractiveness of pulp yield in overcoming a chemical recovery bottleneck is dependent upon a high future profit margin which, as argued in the Introduction of this chapter (Section 3.1), should not be assumed.

3.3.3 Sensitivity analysis

In calculating economic weights all input variables (component costs, rotation length, discount rate, etc. - Table 3.1) were given an appropriate value. To investigate the sensitivity of derived weights to changes in the input variables, the production function (Eqn. 3.4) was subjected to a sensitivity analysis by examining the correlation between economic weights (after James 1982) derived from different component costs. Even a large change in any parameter individually (from -40% to +40% of assumed value), whilst having influence on the expected gains in the case of discount rate and rotation length, had minimal effect on the selection decisions made, with correlations between breeding objectives of extremes consistently above 0.99. Robustness of breeding objectives to variation in cost structure have been previously reported by Smith *et al.* (1986) and Borralho *et al.* (1993).

Increasing the discount rate (Figure 3.2) or decreasing the rotation length have the effect of reducing the importance of future costs (harvesting, transport, and pulping) in comparison to the costs of plantation establishment. Since *DENS* and *PY* have major effect on these future costs,

whilst *VOL* primarily influences growing costs, increasing the discount rate decreases the relative importance of *DENS* and *PY* in comparison to *VOL* (Figure 3.2).

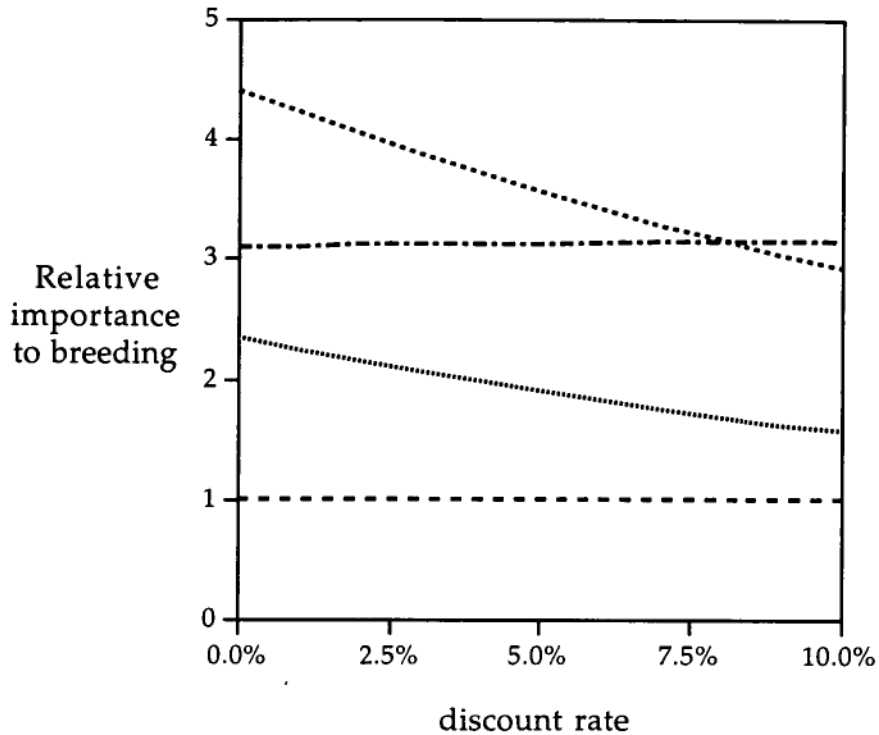

Figure 3.2: The relative importance to breeding (after Eqn. 3.9) of *DENS* (.....); *VOL* (-.-.-.); *PY* (.....); and *FORM* (- - - -) versus the assumed discount rate. Relative value is expressed in relation to the relative value of *FORM*, i.e. a value of 3.5 equates to the trait being 3.5 times as important as *FORM*.

It must be noted that relative importance for breeding is dependent on the degree of exploitable variation in a trait (σ_a), the accuracy of selecting for a trait (approximated here by h), and the degree of correlation with other traits of importance. Whilst the genetic parameters used in this analysis (Table 3.2) are typical of temperate eucalypts, different values of these parameters have also been reported. Changes in genetic parameters will not influence the derived economic weights, but may alter the relative importance of each trait to breeding.

3.3.4 Improvements in the production function

Rotation length has been treated as a fixed input parameter in this analysis. However, genetic improvement may alter the optimum rotation length (Löfgren 1985) and rotation length should thus be considered as an output variable. In considering volume production alone, optimum rotation length can be shown to be dependent upon growth rate and its changes throughout the rotation, the costs incurred, the returns which can be realised from harvesting at different ages, and the discount rate (see Jonsson and Jonsson 1992 for a discussion). If the changes occurring in the objective traits with increasing plantation age can be accurately modelled, an optimum rotation age which minimises the total long-term cost of pulp could be predicted for each genotype. Genotypes would then be chosen for minimum total long-term pulp-cost, with the optimum rotation length associated with the chosen genotypes being an output of the selection process.

Similarly, plantation establishment and maintenance costs have been assumed in this analysis to be fixed, yet genetic improvemant may alter these costs: genetically improved plants may be more expensive increasing establishment costs, whilst faster growing plants may require less weed control. The magnitude of these changes have been assumed to be small, having insignificant effect on the conclusions drawn from this analysis: the correlation between economic weights generated from establishment and maintenance costs of 60% and 140% of assumed value, is 1.00.

3.3.5 The cost of land-use

This analysis has considered the cost of land to be a real cost of growing pulp-wood However, it is not unusual for the cost of land to be considered a *"sunk"* cost and thus be excluded from economic analysis. Whilst it is beyond the scope of this chapter to debate the appropriateness of either approach, the economic weights under a *"free"* land approach, calculated by setting the annual land cost to zero, are *VOL*: \$0.201; *DENS*: \$314; *PY*: \$377; and *FORM* \$1.15, with the relative value to breeding (Eqn. 3.9) of 3.1, 4.1, 2.2, and 1.0 respectively. With no cost of land the total cost of growing pulp-wood is reduced in relation to the total cost of harvesting, transport, and pulping, and as *VOL* primarily influences growing cost, the relative value of *VOL* is reduced in relation to *DENS* and *PY*, those traits having influence upon later processing costs.

3.3.6 From pulp to paper

The breeding objective defined here considered only the minimisation of the total cost of producing unbleached kraft pulp, but pulp is used to make paper and the influence of quantifiable traits on the cost of bleaching and the cost of converting pulp into paper cannot be ignored.

Paper strength may decline at higher levels of wood density (Arbuthnot 1991, Ikemori *et al.* 1986, Higgins 1984) however Arbuthnot (1991) also demonstrated that increasing the intensity of pulp refining may negate the effect. Pulp yield may show a positive relationship with paper strength and less pulp may be required from trees of higher pulp yield to achieve a given paper strength (Dean 1995). However, some paper products, for example high brightness printing paper, are limited by requirements of paper bulk and opacity rather than requirements of strength, and increasing paper strength offers no advantage. Other traits such as fibre length may be important for paper strength (Campinhos and Claudio da Silva 1990, Zobel and van Buijtenen 1989).

If biological traits under genetic control can be demonstrated to systematically influence the cost of converting unbleached pulp to paper, the production function (Eqn. 3.4) should be expanded to include such relationships. To date, however, little has been published which allows the construction of reliable relationships. In this chapter I have conservatively assumed that *VOL*, *DENS*, *PY* and *FORM*, have no quantifiable effect on the cost of converting unbleached pulp to paper.

3.3.7 Traits used in the objective

The biological traits used in this study, *VOL*, *DENS*, *PY* and *FORM* are themselves aggregate traits, potentially masking aspects of the relationships between biological traits and the breeding objective. As an example, both *DENS* and *PY* can be increased in ways which are not beneficial for a paper end-use: tension-wood has both a higher *DENS* and *PY* than normal wood, but fibre from tension-wood is relatively unsuitable for paper-making (Smook 1992). Further, *PY* is both a characteristic of processing and biology: whilst *PY* shows strong correlation with cellulose content (Wallis *et al.* 1995), it can be improved by uniformity of chip size or by increasing the residual lignin content (kappa number) of produced pulp (e.g. Crane *et al.* 1987). Yet the gross effect of *DENS* and *PY* on pulp-cost has been demonstrated

theoretically in Chapter 2 and empirically by Campinhos and Claudio da Silva (1990) and thus both traits should be included in the objective.

Stem form clearly has little effect on the total cost of producing kraft pulp (Figure 3.1) and including form as an additional trait in a multi-trait objective does not improve expected gains. Other traits such as resistance to frost (Raymond *et al.* 1992) or drought (Dutkowski 1995) can have considerable effect on tree growth in some regions, whilst there are many properties of wood such as the syringyl:guaiacyl composition of lignin (Tsutsumi *et al.* 1995) which may alter the cost effectiveness of the pulping process. Inclusion of a trait in the objective, however, requires that mathematical relationship between the trait and the cost of producing pulp can be defined. Whilst techniques exist for inclusion of traits in the absence of sufficient economic and biological data (e.g. Woolaston 1994, Dean *et al.* 1986) these techniques implicitly assume economic weights which may be far from realistic (Gibson and Kennedy 1990).

3.3.8 A common objective for all growers

Growers of pulp-wood who sell roundwood on the basis of green volume may view their objective as the minimisation of the cost of growing a unit of green volume. Similarly, wood-chip mills which sell pulp-wood chips on the basis of dry weight may wish to minimise the cost of a unit of dry material (e.g. Borralho *et al.* 1992c, Bridgwater *et al.* 1983). Brascamp *et al.* (1985) and Smith *et al.* (1986) demonstrated that breeding objectives for animal production in a competitive market are similar for both producers and consumers when the production systems are correctly modelled. Likewise, all growers of eucalypt plantations for kraft pulp should have the same objective - minimise the total cost of producing pulp. Whilst consumers (pulp-mills) may currently purchase pulp-wood on the basis of dry weight or green volume, the negotiated price reflects a mill's ability to process the material into pulp or paper in an open competitive market. Any technological change due to breeding undertaken by a grower which has a detrimental effect on the ability of a mill to manufacture paper at competitive prices will result in a reduction of the purchase price, potentially resulting in losses for the grower.

3.4 CONCLUSION

The key traits which influence the total cost of producing unbleached eucalypt kraft pulp are density and standing volume at harvest, accounting for 95% of the gain possible using a selection criterion involving density, volume, pulp yield, and stem form. Selection for pulp yield alone provides approximately 50% of the gain possible from selection for either density or standing volume. Stem-form has only minimal effect on the cost of producing pulp.

APPENDIX 3.1 - Value to breeding

If traits in the breeding objective are genetically and phenotypically related, as given by non-zero off-diagonal elements in the **A** and **P** matrices (Eqn. 3.6), then selection for a single trait will result in a correlated gain in other objective traits. The resulting change in the objective is dependent upon the extent and direction of the genetic relationships, and the economic weights of the correlated traits. Gain towards the breeding objective (G) from index selection (e.g. Cotterill and Dean 1990) is given by:

[A3.1-1] $$G \propto \sigma_I$$

where σ_I is the square-root of the variance of the selection index (σ^2_I), given as:

[A3.1-2] $$\sigma_I^2 = \mathbf{w}\mathbf{A}'\mathbf{P}^{-1}\mathbf{A}\mathbf{w}'$$

where **w** is the vector of economic weights for traits in the objective; **A** is an additive covariance matrix relating the selection traits with traits in the objective; and **P** is a phenotypic relationship matrix for the selection traits. When selecting for a single trait (t) **P** becomes the phenotypic variance of the selection trait ($\sigma_{p.t}$), **A** becomes an additive covariance vector relating the trait being selected to each trait in the objective ($\mathbf{a}_{t.a}$), and thus gain towards the objective for single-trait selection for the t^{th} trait (G_t) becomes:

[A3.1-3] $$G_t \propto \frac{\mathbf{a}_{t.a}\mathbf{w}}{\sigma_{p.t}}$$

Chapter 4:

Assumptions underlying the use of economic weights - are they valid in breeding for eucalypt kraft pulp?

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4.1 INTRODUCTION

Ponzoni (1986) divided the determination of a breeding objective into four stages: (1) the specification of the production system; (2) identification of sources of income and costs; (3) identification of the biological traits influencing income and costs; and (4) determination of the economic value or weight of each trait in the objective.

In Chapter 3 Ponzoni's (1986) method was used to derive a breeding objective for minimising the total cost of producing unbleached eucalypt kraft pulp. The biological traits identified as having impact on the cost of producing kraft pulp were standing volume at harvest (incorporating growth and survival), basic density, pulp yield, and stem form. Chapter 3 presented economic weights for these traits.

Whilst economic weights are commonly reported as absolute values (e.g. Dean *et al.* 1990, Chapter 3), they are an interpretation of an economic production function at nominal trait levels. Underlying the application of economic weights in the prediction of genetic gain are the assumptions of:

• *linearity*: that the slope of the production function is constant over the exploitable range of the trait; and

• *independence between traits*: that the economic weight for one trait is independent of the levels of other traits in the objective - i.e. that the product of the economic weights and the trait values are additive.

In breeding plantation eucalypts, populations are often large and selection intensities high: selection of the best 50 individuals from 5000 trees in a base population is a common scenario. The assumptions underlying the application of production functions via economic weights may well break-down at such extreme selection pressures.

This chapter will examine the assumptions of linearity and independence using as the breeding objective the production function derived in Chapter 3 for minimising the total cost of producing unbleached eucalypt kraft pulp. Assumed genetic parameters and selection intensities will be values applicable to selecting from early generation eucalypt populations. An alternative method of gain determination will be proposed which avoids errors due to non-linearity and interdependence between traits in the production function.

4.2 METHODS

4.2.1 Biological traits in the objective

The biological traits used in the breeding objective cost function described in Chapter 3 for the minimisation of the total cost of unbleached eucalypt kraft pulp are:

standing volume at harvest (*VOL*): the green volume of timber which can be harvested from a hectare of forest estate at rotation end - this trait incorporates both growth rate and survival and has the units of cubic metres per hectare (assumed population mean 250 m^3 ha^{-1})

basic density at harvest (*DENS*): the dry weight of wood per unit of green volume in oven-dry tonnes (ODt) per cubic metre (assumed population mean 0.5 ODt m^{-3});

pulp yield (*PY*): the oven-dry weight of kraft pulp produced as a fraction of the total dry weight of wood, in oven-dry tonnes of pulp per oven-dry tonnes of wood (assumed population mean 0.5 ODt ODt^{-1}, or 50%); and

stem form (*FORM*): the general form of trees at harvest (subjectively incorporating the straightness of stem and degree of branching) - this trait is defined here as a six point score where a score of six represents very good form and a score of one represents very poor form (assumed population mean score 3.5).

4.2.2 *The breeding objective cost function*

The total pulp-cost function where total pulp-cost (C_{total}), expressed in dollars per oven-dry tonne of unbleached eucalypt kraft pulp ($ ODt^{-1}) discounted to the time of plantation establishment is (after Chapter 3):

$$C_{total} = \frac{[C_{est}]}{(1-loss)} + \frac{[C_{main} + C_{land}]}{(1-loss)} \cdot \left[\frac{1-(1+d)^{-r}}{d}\right] + \frac{[C_{harv} + C_{trans}]}{(1-loss).(1+d)^{r}} + \frac{\left[C_{chip} + C_{dig} + C_{chem} + C_{evap} + C_{rec} + C_{recaust}\right]}{(1+d)^{r}} \quad [4.1]$$

where C_{est} is the cost of plantation establishment; C_{main} is the annual maintenance cost; C_{land} is the annual cost of land; C_{harv} is the cost of harvesting; C_{trans} is the cost of transport; *loss* is the fibre loss in the pulpmill expressed as a fraction of total delivered fibre (assumed to be 5%); r is the rotation length; d is the discount rate; C_{chip} is the cost of chipping; C_{dig} is the cost of digestion; C_{chem} is the cost of chemical other than effective alkali consumed during pulping; C_{evap} is the cost of black-liquor evaporation; C_{rec} is the recovery furnace cost; and $C_{recaust}$ is the cost of recausticizing. All costs are expressed in US dollars per oven-dry tonne of unbleached pulp produced (Table 4.1).

Table 4.1: The cost of each stage of production (in US dollars per oven-dry tonne of unbleached eucalypt kraft pulp i.e. \$ ODt^{-1}) as a function of standing volume at harvest (*VOL*), stem form (*FORM*), pulp yield (*PY*) and density (*DENS*) after Chapter 3. Costs of pulping stages are split into total operating cost and capital cost (*operating/capital*), and numbers in parenthesis are negative.

production stage	cost function - $COST \propto f(VOL, DENS, PY, FORM)$	base cost (\$US per ODt)	timing of cost
cost of land	$C_{land} \propto \frac{1}{VOL.PY.DENS}$	1.6	annual cost
plantation establishment	$C_{est} \propto \frac{1}{VOL.PY.DENS}$	24	rotation start
plantation maintenance	$C_{main} \propto \frac{1}{VOL.PY.DENS}$	1.6	annual cost
harvesting	$C_{harv} \propto \frac{1}{VOL^{0.2}.FORM^{0.1}.PY.DENS}$	80	rotation end
transport	$C_{trans} \propto \frac{1}{PY.DENS}$	40	rotation end
chipping	$C_{chip} \propto \frac{1}{PY}$	20/15	rotation end
digester	$C_{dig} \propto \frac{1}{PY.DENS}$	30/50	rotation end
chemical (excluding EA)	$C_{chem} \propto \frac{1}{PY}$	5/10	rotation end
evaporators	$C_{evap} \propto \frac{\frac{1}{DENS} + 1.6(1-PY) - 0.7}{PY}$	40/15	rotation end
recovery	$C_{rec} \propto \frac{(1-PY)}{PY}$	(50)/35	rotation end
recausticize	$C_{recaust} \propto \frac{(1-PY)}{PY}$	15/15	rotation end

The cost of each stage should include a component of "normal" profit (Brascamp *et al.* 1985), and pulp-mill capital costs (Table 4.1) are considered to be related to variable costs to the power of 0.6 (Wilson 1950). The annual discount rate and rotation length used are 5% and 15 years respectively.

4.2.3 Economic Weights

The economic weight of a biological trait can be defined as the change in the breeding objective (savings in total pulp cost) associated with a unit increase in that trait, calculated at the population mean. However, a unit increase in *PY* represents an increase from 0.5 ODt ODt^{-1} to a non-sensical 1.5 ODt ODt^{-1} (the mass of pulp per unit mass of wood cannot exceed 1 ODt ODt^{-1}). To overcome differences in the units and expected ranges of each trait savings in total pulp cost were calculated over an increase of 0.1 σ_a for each trait (Table 4.2 below), and economic weights ($ per unit change) determined by dividing the observed savings by 0.1 σ_a.

Gain towards the breeding objective can be estimated for each tree by multiplying the respective economic weights by the observed estimates of genetic worth for each trait (given as deviations from the population mean), expressed in matrix notation as:

[4.2] $G = \mathbf{a}_0 . \mathbf{v}$

where G is the gain in savings in total pulp cost ($ per ODt) for an individual tree; $\mathbf{a}_0$ is a vector of the estimated breeding values for the objective traits for the individual tree expressed as deviations from the respective population means; and $\mathbf{v}$ is a vector of the economic weights for the objective traits.

4.2.4 Data set

To compare gain predicted via (i) economic weights (Eqn. 4.2) and (ii) gain determination via direct substitution into the breeding objective cost function (Eqn. 4.1), fifty 5000 record data-sets of breeding values were simulated using the Monte-Carlo method. Breeding-values of the four traits in the breeding objective ($\mathbf{a}_0$ - Eqn. 4.2) were randomly generated assuming the genetic parameters presented in Table 4.2. The gain due to direct selection on breeding values was taken as the mean of the gains due to selection observed for each of the 50 data-sets individually.

Table 4.2: Means, additive standard deviations (diagonal), and genetic correlations (upper diagonal) used in generation of the simulated data. Parameters were based upon Dean *et al.* (1990), Chapter 5, and Australian Paper Plantations Pty. Ltd. unpublished data and are typical of early generation *E. globulus* or *E. nitens* populations.

	unit	mean	*VOL*	*DENS*	*PY*	*FORM*
VOL	$m^3\ ha^{-1}$	250	38	0.1	0.1	0.4
DENS	$t\ m^{-3}$	0.5		0.022	0.3	0
PY	$t\ t^{-1}$	0.5			0.0077	0
FORM	score 1...6	3.5				0.36

4.3 RESULTS AND DISCUSSION

4.3.1 Linearity

The linearity of cost function response to changes in the breeding objective traits was examined by determining the economic weight for each trait at the expected trait mean and at deviations from the mean equivalent to selecting either the highest or lowest 1% of the population to simulate the *extremes* of selection pressure which may be applied in a breeding program (e.g. selection of the best 50 trees from a population of 5000).

Table 4.3: Economic weights for traits in the breeding objective calculated at the population mean (pop^n mean) and at the mean of the highest and lowest 1% of the population.

trait	unit	Economic Weight		
		lowest 1%	pop^n mean	highest 1%
VOL	$\$\ (m^3\ ha^{-1})^{-1}$	0.730	0.269	0.142
DENS	$\$\ (ODt\ m^{-3})^{-1}$	432	349	289
PY	$\$\ (ODt\ ODt^{-1})^{-1}$	438	411	388
FORM	$\$\ (score\ 1...6)^{-1}$	1.59	1.15	0.90

For each trait the economic weight declined with increase in the trait. The observed decline in the economic weights with increase in the value of each trait through the selectable range (from the mean of the lowest 1% to the mean of the highest 1%) represents a decline in the slope of the cost-response curve (depicted in Figure 4.1 for *VOL*). The observed responses are typical of a cost function where cost is proportional to the inverse of the value of a trait:

$$[4.3] \qquad Cost \propto \frac{1}{trait}$$

where *Cost* is the cost (per ODt of pulp produced) of a stage in production; and *trait* is the value of a given trait. Inverse relationships of this kind predominate in the assumed total-pulp cost function (Table 4.1).

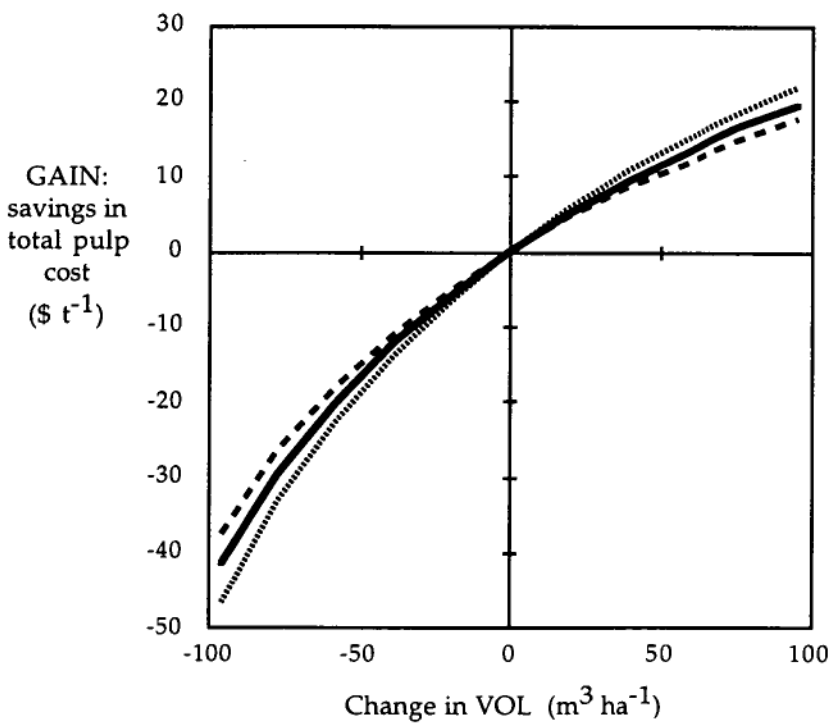

Figure 4.1: Response towards the breeding objective (Eqn. 4.1) due to changes in *VOL* (standing volume at harvest expressed as deviations from the mean of 250 m^3 ha^{-1}), for three levels of *DENS* (basic density at harvest), -0.055 ODt m^{-3} (.....), 0 (——), and +0.055 ODt m^{-3} (- - - -). The depicted range of change in *VOL* (±100 m^3 ha^{-1}) and *DENS* (±0.055 ODt m^{-3}) represent the extremes of gain which could be expected due to selection for either trait. The horizontal axis (Change in *VOL*) represents the breeding value of an individual expressed as a deviation from the population mean.

VOL shows the greatest non-linearity over the range of exploitable genetic variation, and *PY* the least. Whilst these results somewhat reflect the effect of each trait upon the production function (Equation 4.1) they predominantly reflect the relative coefficients of genetic variation (the ratio of the additive variation to the mean): 15% for *VOL* and 1.5% for *PY*.

If gain (after Eqn. 4.2) is predicted using fixed economic weights calculated at the population mean, gain will be over-estimated for individuals with breeding values either above or below the population mean: for individuals with positive breeding values (breeding values above the mean) the *true* economic weights are lower than the economic weights calculated at the population mean and thus gain is over-estimated; and at negative breeding values (breeding values below the mean) the *true* economic weights are higher than the economic weights calculated at the population mean and thus individuals are not predicted to be as poor as they actually are.

4.3.2 Independence between traits

If traits in the cost function are independent, the value of an increase in a trait (specified as the economic weight for that trait) will be independent of the values of other traits in the objective. The economic weights for *VOL* for different levels of *DENS* and *PY* are presented in Table 4.4. Economic weight for *VOL* declines with increase in either *DENS* or *PY*: an outstanding tree (say) with high breeding values for both *DENS* and *PY* (both traits at the extreme of their selectable ranges: 0.059 t m^{-3} and 0.021 t t^{-1} above their respective means) would not gain as much from a given increase in *VOL* (economic weight for *VOL* \$0.231 $(m^3\ ha^{-1})^{-1}$ - Table 4.4) as a tree which has low *DENS* and *PY* (economic weight for *VOL* \$0.319 $(m^3\ ha^{-1})^{-1}$).

Table 4.4: Economic weight for *VOL* versus levels of *DENS* and *PY* (levels of *DENS* and *PY* represent the mean of the highest and lowest 1% for each trait in the population).

Eco. Weight *VOL* ($ $(m^3\ ha^{-1})^{-1}$)		*DENS* (ODt m^{-3})		
		lowest 1%	pop^n mean	highest 1%
PY (ODt ODt^{-1})	lowest 1%	0.319	0.281	0.251
	pop^n mean	0.306	0.269	0.241
	highest 1%	0.294	0.259	0.231

The influence of *DENS* on the value of *VOL* is graphically depicted in Figure 4.1. At low levels of *DENS* (0.055 ODt m^{-3} below the population mean for *DENS*) the economic weight for *VOL* is higher than at high levels of *DENS* (+0.055 ODt m^{-3}).

The observed inderdependence between traits has the implication that an individual tree having high breeding values for more than one trait would not be as valuable as it appears if gain is calculated using a fixed set of economic weights (Eqn. 4.2).

4.3.3 Implications

The value (savings in total pulp cost) of an increase in a trait not only declines at high levels of that trait (e.g. trees of high *VOL* are not as valuable as they appear), but the value from a given level of *VOL* (for example) also declines if other traits in the objective are also high (Table 4.4).

To quantify the effect of the observed non-linearity and inter-dependence, a range of selection-pressures were applied to the simulated data-sets. Selection was made on the basis of a linear combination of economic weights and the simulated breeding values for all traits in the objective (after Eqn. 4.2):

$$[4.4] \quad G = 0.269(VOL_a) + 349(DENS_a) + 411(PY_a) + 1.15(FORM_a)$$

where *G* is the gain towards the objective (reduction in total pulp cost discounted to the time of plantation establishment) and VOL_a, $DENS_a$, PY_a and $FORM_a$ are the breeding values of *VOL*, *DENS*, *PY* and *FORM* at harvest expressed as deviations from the respective population means ($\mathbf{a}_o$ - Eqn. 4.2). The "*true*" value of each tree in the simulated data-set was determined by directly substituting the simulated breeding values into the cost function (Eqn. 4.1). The gain overestimate due to prediction by economic weights, calculated as the difference between the economic weight gain and the *true* gain, divided by the *true* gain, is presented in Table 4.5 for selection of the best 1% of trees, and in Figure 4.2 against the proportion of the population selected.

Table 4.5: Expected gain due to selection of 1% of a population of 5000 trees on the basis of minimum total pulp cost. Pulp costs are expressed as expected savings at rotation end (bigger is better).

	gain	units
VOL	80.5	$m^3\ ha^{-1}$
DENS	0.04	$ODt\ m^{-3}$
PY	0.88	% ($ODt\ ODt^{-1}$)
FORM	0.24	points
pulp cost (using eco. weights Eqn. 4.2)	83	$\$\ ODt^{-1}$
"true" pulp cost (Eqn. 4.1)	66	$\$\ ODt^{-1}$
difference	16	$\$\ ODt^{-1}$
difference	25	%

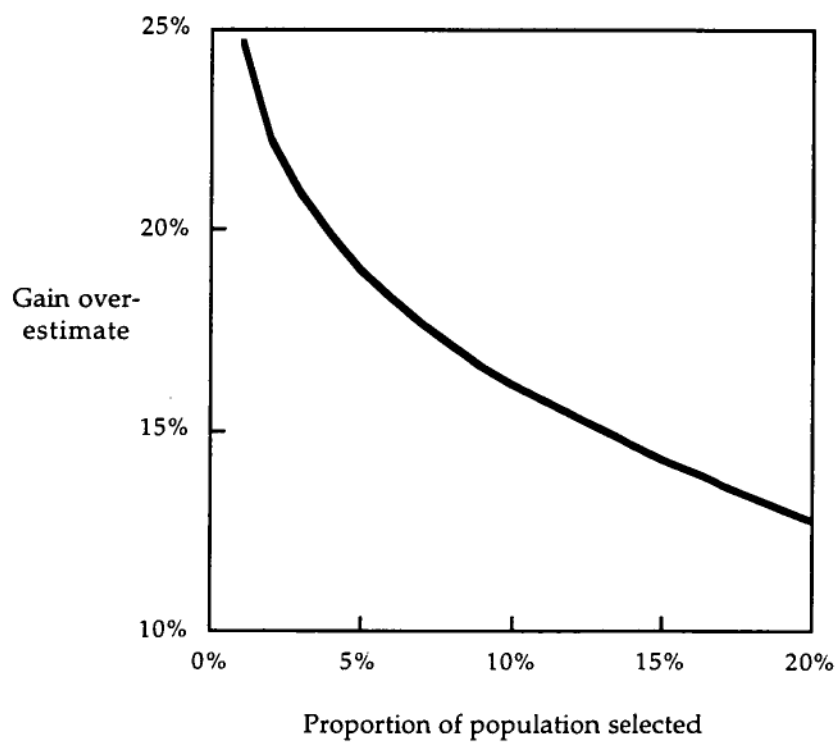

Figure 4.2: Over-estimate in gain towards the objective from use of economic weights (calculated as the difference between the economic weight gain and the *true* gain, divided by the *true* gain) versus the proportion of the population selected.

As predicted, the degree to which expected gain is over-estimated when economic weights are used in the prediction of gain increases as the proportion of the population selected decreases - and when 1% of the population is selected the gain is over-estimated by approximately 25% - or $16 per ODt of pulp produced (Table 4.5).

There has been considerable debate, mainly amongst animal breeders, as to relevance and difficulties of non-linear production functions (Harris 1970, Goddard 1983, Brascamp *et al.* 1985, Smith *et al.* 1986, Groen *et al.* 1995). However, the effect of non-linearity and interdependence between traits upon the estimated gain (or rather the over-estimation of gain) depends largely on the degree of exploitable variation and the intensity of selection pressure applied. *VOL* shows considerable exploitable genetic variation and a considerable change in economic weight over the exploitable range, whereas *PY* has a much lower relative variation and more consistent economic weight. The selection pressure applied to a population (the proportion of the population selected for further breeding or deployment) influences the error in predicting gain from using economic weights (Figure 4.2).

The gain overestimate depicted in Figure 4.2 is based upon genetic variations expected in early generation temperate eucalypt populations, and the range of selection intensities are representative of selection pressures which may be applied in early stages of breeding programs (selection of 50 individuals from 5000 is not uncommon). Moderate selection intensities applied to populations with reduced degrees of exploitable variation (as may be common in more advanced generation breeding) may not result in such appreciable gain over-estimation due to the use of fixed economic weights. A further consideration is that the use of economic weights only overestimates gain - it does not significantly alter the ranking of individuals in large populations. However, if breeders are using cost-benefit analysis in decision making, the potential overestimate in gain may warrant consideration.

Whilst all traits in the breeding objective show a decline in economic weight with increasing trait value (Table 4.3), there is no evidence to suggest that the cost function (Eqn. 4.1) will show a negative economic weight (an increase in total pulp cost with increase in a biological trait) at high levels of any trait in the objective. Cost functions which show change in sign of economic weight with increasing trait level have an optimum level above which further

increase in a trait reduces profitability (e.g. Amer *et al.* 1994). The breeding objective under examination is the minimisation of the cost of producing unbleached kraft pulp. *DENS* and *PY* have been demonstrated to influence the properties of paper produced from pulp (Higgins 1984, Ikemori *et al.* 1986, Arbuthnot 1991, Dean 1995) and should the breeding objective be expanded to include conversion of pulp to paper, a decline in the value of paper with increasing *DENS* (say) may produce a negative influence on the economic worth of *DENS* at high levels. To date, however, little has been published which allows the construction of reliable relationships between traits used in the breeding objective and the costs of converting pulp to paper.

Harris (1970) pointed out that errors due to use of a non-linear objective function could be completely negated if breeding values of the objective traits could be directly substituted into the objective cost function. However, traits in the presented breeding objective (*VOL*, *DENS*, *PY*, and *FORM* at the time of harvest) are rarely directly assessed in tree breeding programs. Instead, these traits are indirectly assessed as (for example) tree diameter at 1.3 m, Pilodyn penetration at 1.3 m (Chapter 5), and *PY* predicted using Near Infrared Reflectance Analysis (Michell and Schimleck 1995), and usually these traits are assessed at an age earlier than expected harvest age. Selections are made by estimating breeding values for each selection trait and tree using BLP or BLUP techniques (e.g. White and Hodge 1989). Economic weights for the selection traits (vector **b**) can be derived from economic weightings for traits in the breeding objective (vector **v**, Eqn. 4.2) after (Schneeberger *et al.* 1992):

$$[4.5] \quad \mathbf{b} = \mathbf{G}_{11}^{-1}.\mathbf{G}_{12}.\mathbf{v}$$

where $\mathbf{G}_{11}$ is the genetic variance-covariance matrix of the selection traits and $\mathbf{G}_{12}$ is the genetic covariance matrix between the selection traits and the traits in the objective - both assumed to be known without error. If the economic weights are assumed to be constant across the range of a trait the value of each tree, expressed in the units of the breeding objective (e.g. dollars per oven-dry tonne of unbleached eucalypt kraft pulp), is then determined after:

$$[4.6] \quad G = \mathbf{a}_s.\mathbf{b}$$

where G is the gain in savings in total pulp cost ($ per ODt) for an individual tree; $\mathbf{a}_s$ is a vector of the estimated breeding values for the selection traits for the individual tree expressed as deviations from the respective population means; and **b** is a vector of the economic weights for the selection traits. Trees are then selected on the basis of maximum expected gain. This method does not, however, overcome the problems of gain over-estimation due to non-linearity of cost function.

Alternatively, the $\mathbf{G}_{11}$ and $\mathbf{G}_{12}$ parameters may be used to predict, by tree, breeding values for the breeding objective traits (vector $\mathbf{a}_o$) from the known selection trait breeding values (vector $\mathbf{a}_s$) after:

$$[4.7] \quad \mathbf{a}_o = \mathbf{G}_{12}' . \mathbf{G}_{11}^{-1} . \mathbf{a}_s$$

The individual-tree values for each breeding objective trait can then be directly substituted into the breeding objective cost function (Eqn. 4.1) providing an estimate of gain which is free of the distortions of cost-function non-linearity and trait interdependence.

It must be noted that this method is computationally more difficult than prediction via economic weights as the set of selection trait estimates must be converted to objective trait estimates *for each tree individually* before being substituted into the relatively complex objective cost function. But even with large data sets the computing task is today relatively minor.

4.4 CONCLUSIONS

There is observable non-linearity between total pulp-cost and the levels of all traits in the breeding objective cost function examined, and the true economic weight for each trait declines at higher values of each trait. The breeding objective function examined also shows interdependence between traits in the objective - that is, the economic weight for one trait is dependent upon the actual value of other traits. These effects result in the expected gains (towards reducing the total cost of unbleached eucalypt kraft pulp) being overestimated. The error was greater at high selection intensities: when the best 1% of a population is selected, expected gain may be over-estimated by 25%.

It is suggested that the use of economic weights for prediction of gain may be inappropriate where exploitable variation is great and intensity of selection high. An alternative method of gain determination is proposed: predicted values of selection traits are used to generate values for breeding objective traits which are then substituted directly into the breeding objective cost function thus avoiding errors associated with non-linearity and interdependence.

Chapter 5:

Use of a Pilodyn for the indirect selection of basic density in *Eucalyptus nitens*

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5.1 INTRODUCTION

Basic density (hereafter referred to as density) is dry weight of wood per unit of green volume. It comprises a complex of characteristics such as the ratio of earlywood to latewood, cell wall thickness, cell diameter, and lignin content (King *et al.* 1988). Wood density shows useful correlation with some important commercial traits such as wood consumption, moisture content, pulp and paper properties, and sawn timber properties (Bunn 1981, Wang *et al.* 1984, Zobel and van Buijtenen 1989, Dean *et al.* 1990, Arbuthnot 1991, Borralho *et al.* 1993, Chapters 2 & 3).

One obvious advantage of incorporating wood density as a selection trait is its apparent strong genetic control, with heritabilities in eucalypts of between 0.6 and 0.8 being reported by many authors (Otegbeye and Kellison 1980, Wang *et al.* 1984, Matheson *et al.* 1986, Dean *et al.* 1990, Borralho *et al.* 1992c, Eldridge *et al.* 1993). Yet direct selection for density in breeding programs requires the removal and analysis of timber samples either in the form of increment cores or disks, work which can be very costly for large numbers of samples and which may result in the death of sampled trees.

The Pilodyn is a hand-held instrument which drives, with a known force, a high precision hardened-steel flat-nosed pin into a wood sample.

Depth of pin penetration is read directly from a scale on the top of the instrument. The Pilodyn was originally developed to measure the shock resistance of wood in service and assess the degree of soft rot in power transmission poles (Hoffmeyer 1978), but it has shown promise as an indirect measure of wood density in standing trees (Moura *et al.* 1987, Cown 1978).

There is now considerable evidence in conifers that the correspondence between Pilodyn and density is good. In 12-year-old Douglas fir Pilodyn penetration showed a genetic correlation with density of -0.95 (King *et al.* 1988). In Loblolly pine at age 20 the genetic correlation between Pilodyn and density was -0.8 (Sprague *et al.* 1983). There have been fewer studies in eucalypts but genetic correlations between Pilodyn and density have been consistently high ranging from -0.48 and -0.93 (Rosado *et al.* 1983, Dean *et al.* 1990). Pilodyn penetration seems to be under strong genetic control in conifers, with reported heritabilities between 0.34 and 0.46 (Nepveu and Velling 1983, Sprague *et al.* 1983, King and Burdon 1991). The only reported heritability for Pilodyn penetration in eucalypts is by Dean *et al.* (1990) with h^2=0.21 in eight year old *Eucalyptus globulus*.

This paper examines the genetic control of Pilodyn penetration and its correlation with wood density in seven-year-old plantation grown *E. nitens*. The application of the Pilodyn for indirect selection of density in eucalypt breeding programs is discussed.

5.2 MATERIALS AND METHODS

5.2.1 Trial sites

Six hundred seven-year-old *E. nitens* trees were sampled from a progeny trial established by Australian Paper Plantations Pty. Ltd. (a member of the Amcor group) on two contrasting sites in eastern Victoria, Australia (Table 5.1). Trees were raised in containers and established using operational practices in July 1986 at a planting density of 1000 stems per hectare (Bennett *et al.* 1989).

Table 5.1: Description of trial sites, site preparation and fertiliser treatment at establishment.

	Site 1	Site 2
Soil	gradational clay-loam	duplex: sandy loam over clay
Latitude (°S)	38	38
Longitude (°E)	146	147
Altitude (m a.s.l.)	200	80
Rainfall (mm yr^{-1})	1006	728
Previous landuse	Radiata pine plantation	agricultural pasture
Site preparation	winged rip, disc plough	ridge plough
Fertiliser at planting (kg ha^{-1})	N 4.2, P 0.9, K 0.9	N 4.2, P 50.9, K 50.9

5.2.2 Field design

Both trial sites were established as 40 randomised complete blocks, each composed of 104 single-tree plots (including 94 trial families and 10 *"control"* commercial seedlots), giving a total of 40 trees per family per site. The trees sampled for Pilodyn and density were primarily harvested from six blocks on each site.

5.2.3 Genetic material

The 94 open-pollinated families included in the trial are from six collection areas (Table 5.2), five of the Toorongo provenance and one of the Rubicon provenance, as classified by Pederick (1979). Provenances were included in the trial on the basis of previously reported growth and tree-form (Pederick 1986). Of the 94 families, the 50 families with the greatest diameter at age seven were sampled for Pilodyn, density, and pulp and paper property evaluation, a planned sample of 300 trees from each site (but less due to mission values).

Table 5.2: Seed origin of the genetic material in the sampled progeny trial. "Families in top 50" shows the number of families from each collection area which were sampled for Pilodyn and wood-property traits.

Collection area	Provenance	Latitude (°S)	Longitude (°E)	Altitude (m a.s.l.)	Rainfall (mm p.a.)	Families in trial	Families in top 50
1	Toorongo	38	146	1240	1400	20	5
2	Rubicon	37	144	1000	1200	8	4
3	Toorongo	38	146	800	1400	5	2
4	Toorongo	38	146	1200	1400	24	16
5	Toorongo	38	146	400	1400	19	9
6	Toorongo	38	146	800	1400	18	14

5.2.4 Measurements

Pilodyn measurements were taken prior to falling using a 6J Forest Pilodyn (manufactured by Proceq SA, Zürich). A total of eight observations were made at 1.3 m on each tree, two observations on each of the North, South, East and West cardinal aspects. At each aspect a 5 cm diameter section of bark was removed to expose the cambial surface for the Pilodyn readings. After felling, each tree was measured for total height, merchantable height (height to 5 cm under-bark diameter), diameter at 1.3 m, and diameter at 15%, and 35% of total height. Individual tree volume was calculated as the sum of the sectional volumes, with each sectional volume calculated as a section of a cone.

A 10 cm thick disk was cut from each tree from a height of 1.3 metres. Each disk was sealed in plastic to minimise desiccation, and stored at -18°C until analysis. Family *"whole-tree"* density was determined from four half-stem samples taken from each tree, each 40 cm long: the first immediately above the ground; the second immediately below merchantable height; and the remaining two evenly spaced between the upper- and lower-most samples. The half-stem samples alternated from one side of the tree (as felled) to the other up the stem. All samples were aggregated by family and site (forming a total of 100 aggregate samples - 50 families by two sites) and chipped for analysis of wood, pulp and paper properties. Wood densities for the 1.3 m disks and a 100 g sample of the

aggregate *"whole-tree"* chips were determined using the water displacement method (TAPPI 1989).

5.2.5 Statistical analysis

Correlation and analysis of regression between basic density at 1.3 m (from disks) and the aggregate *whole-tree* density was calculated using the 100 aggregate values, using SAS GLM and SAS REG procedures (SAS Institute Inc. 1989).

The model used for the univariate (Pilodyn only) or bivariate analysis of variance components (Pilodyn and disk density) was, in matrix notation:

[5.1] $\mathbf{y} = \mathbf{Xb} + \mathbf{Za} + \mathbf{e}$

where **y** is the vector of observations for one or both traits, **b** is the vector of fixed effects (replicates within site, seed collection area, and aspect for Pilodyn penetration), **a** is the vector of additive genetic values of trees, **e** is the vector of residuals and **X** and **Z** are incidence matrices relating observations to the effects in the model. The means and (co)variances of the random terms in the model were assumed to be the following:

[5.2] $$E\begin{bmatrix}\mathbf{y}\\ \mathbf{e}\\ \mathbf{a}\end{bmatrix} = \begin{bmatrix}\mathbf{Xb}\\ 0\\ 0\end{bmatrix}, Var\begin{bmatrix}\mathbf{y}\\ \mathbf{e}\\ \mathbf{a}\end{bmatrix} = \begin{bmatrix}\mathbf{V} & \mathbf{R} & \mathbf{ZG}_a\\ \mathbf{R} & \mathbf{R} & 0\\ \mathbf{G}_a\mathbf{Z}' & 0 & \mathbf{G}_a\end{bmatrix}$$

where:

$\mathbf{V} = \mathbf{ZG}_a\mathbf{Z}' + \mathbf{R}$

$\mathbf{R} = \bigoplus_{j=1}^{m} \mathbf{R}_{oj}$ with m=number of records;

$\mathbf{G}_a = \mathbf{A} \otimes \mathbf{G}_{oa}$

A = numerator relationship matrix;

$\mathbf{G}_{oa}$ = variance covariance matrix for the additive genetic effects;

$\mathbf{R}_{oj}$ = residual covariance matrix for tree j;

$\otimes$ = Kronecker product; and

$\oplus$ = direct sum.

Estimates of variance components were calculated using a derivative-free REML algorithm, as described by Graser *et al.* (1987) for one random factor

and expanded for additional random factors by Meyer (1989). Program DFREML (Meyer 1991) was used to carry out the analysis.

The DFREML analysis for wood density did not converge, due to estimates tending to lie outside of the allowable parameter space (i.e. heritabilities larger than 1). To overcome this problem the variance components for density were estimated using a parent (family) model (Henderson 1984):

[5.3] $\mathbf{y} = \mathbf{Xb} + \mathbf{Zf} + \mathbf{w}$

where **f** is the female parent random effect (or open pollinated family) and **w** is the residual (or within family) error. The variance components for the random terms were estimated using the SAS VARCOMP-REML procedure (SAS Institute Inc. 1990). Heritability (h^2) was calculated as:

[5.4] $$h^2 = \frac{\sigma_f^2}{r\left(\sigma_f^2 + \sigma_w^2\right)}$$

where r is the coefficient of relationship; σ^2_w is the within-family variance and σ^2_f is between-family variance. In the case of Pilodyn where convergence was reached, heritabilities were calculated from the model (Eqn. 5.1) as:

[5.5] $$h^2 = \frac{\sigma_a^2}{\sigma_a^2 + \sigma_e^2}$$

where σ^2_a is the additive genetic variance and σ^2_e the error variance. The two models will give comparable estimates of additive and residual variances if a coefficient of relationship (r) of 0.25 for the open-pollinated families is assumed, in which case $\sigma^2_a=4\sigma^2_f$ and $\sigma^2_a+\sigma^2_e=\sigma^2_f+\sigma^2_w$. As related mating in open-pollinated eucalypts may be considerable, a more realistic value for the coefficient of relationship should be between 0.4 (e.g. Volker *et al.* 1990) and 0.54 (Cameron and Cotterill 1989). To allow a comparison with previous studies a value of r=0.4 was used in the calculation of individual tree heritability from DFREML, using the following relationship:

[5.6] $$h^2_{op} = h^2 \frac{0.25}{0.40}$$

where h^2_{op} is the adjusted individual tree heritability.

Repeatability (ρ) estimates for multiple Pilodyn observations were obtained using the relationship (Falconer 1989):

$$[5.7] \quad \rho = \frac{\sigma^2_{bt}}{\sigma^2_{bt} + \sigma^2_{wt}}$$

where σ^2_{bt} is the between tree variance and σ^2_{wt} is the within-tree variance.

5.2.6 Gain from index selection

The expected gain in basic density from selection on an index combining individual and family-mean information for Pilodyn or an index combining individual and family-mean information for disk density was calculated using the formula (after Nicholas 1987):

$$[5.8] \quad GD(\%) = \frac{i\, r_{AC}\, \sigma_a}{\mu_D}\%$$

where: GD is the relative gain in density (%); i is the standardised selection differential; r_{AC} is the accuracy of selection; σ_a is the additive standard deviation of density; and μ_D is the mean density of the unimproved population.

5.3 RESULTS AND DISCUSSION

Basic statistics of Pilodyn penetration and disk density measurements taken at 1.3 m and the family mean *whole-tree* density observations are given in Table 5.3. Variation in Pilodyn was considerably larger (CV=17%) than variation in disk density (CV=10%). The variation (and range of values) in *whole-tree* density was smaller because observations are a pooled sample of six trees. Nevertheless, mean *whole-tree* density was similar to mean disk density, at around 0.505 t m^{-3}.

Table 5.3: Number of observations (n), mean, minimum and maximum values and standard deviation for Pilodyn penetration at 1.3 m, disk density at 1.3 m, and aggregate family *whole-tree* density (based on six-tree family aggregate samples).

trait	n	mean	min	max	s.d.	units
Pilodyn	4681	10.6	5	17	1.84	(mm)
Density - 1.3 m disk	581	0.506	0.390	0.632	0.050	(t m^{-3})
Density - "*whole-tree*"	100	0.505	0.433	0.575	-	(t m^{-3})

The relationship between the aggregated 1.3 m disk density, taken as the mean of six trees (weighted by volume), and the aggregate *whole-tree* density is shown in Figure 5.1. It is apparent that a strong linear relationship exists (with $r^2 = 0.93$) between density at 1.3 m and the *whole-tree*. There was no significant improvement in the fit of the regression ($p_{improvement}<0.05$) if either family or site were included as class variables. Also, the slope of the regression line did not differ significantly ($p_{difference}<0.05$) across the two sites, despite a marked difference in mean density at each site.

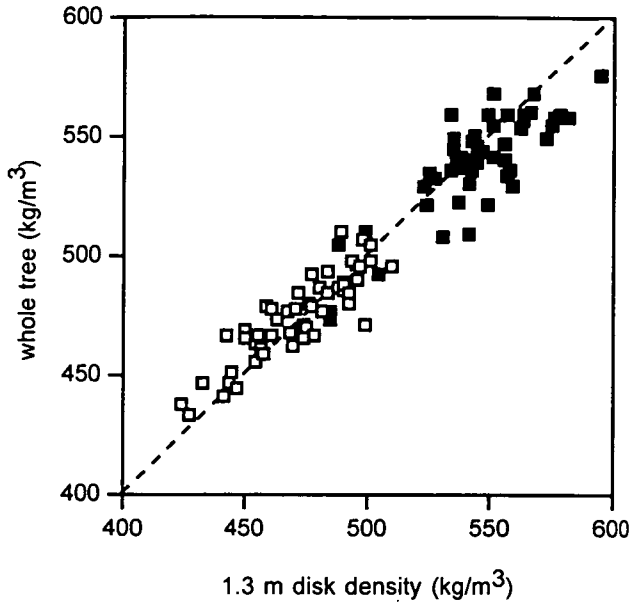

Figure 5.1: Relationship between *whole-tree* density and 1.3 m disk density, for Site 1 (□) and Site 2 (■). Each data-point corresponds to an aggregated sample of 6 half-sib trees.

This result suggests that 1.3 m disk density is an accurate predictor of *whole-tree* density, being relatively independent of site and family. The correlation observed (r=0.96) was based on family within site aggregates, and thus is a lower limit for the genetic correlation (*i.e.* correlation of family means - Burdon 1977). Individual-tree phenotypic correlations would be expected to be lower.

5.3.1 Genetic parameters

Heritability for Pilodyn penetration (individual observation) was 0.46 (Table 5.4) when combining data from all four aspects (eight observations per tree), and 0.60 when only two observations from one aspect were considered. Genetic correlations between Pilodyn penetration and disk density were high (above -0.87). The results are presented in Table 5.4.

Table 5.4: Heritabilities of a single Pilodyn penetration and 1.3 m whole-disk density, and phenotypic (r_p) and genetic (r_g) correlation between these traits. Genetic parameters for Pilodyn were based upon (i) 8 observations per tree (2 on each of 4 aspects), and (ii) two observations per tree from a single aspect (presented results are the simple average of the individual aspect parameters).

	h^2±s.e.	Correlation with density	
	(r=0.4)	r_p	r_g
Pilodyn (8 obs.: 4 aspects, 2 obs./aspect)	0.46 (±0.01)	-0.50	-0.87
Pilodyn (2 obs.: 1 aspect, 2 obs./aspect)	0.60 (±0.01)	-0.59	-0.92
Density (1.3 m, whole disk)	0.73 (±0.09)		

Dean *et al.* (1990) reported a lower heritability for Pilodyn penetration in *E. globulus* (h^2=0.21), but their observed correlation between Pilodyn penetration and density was similarly high (r_g=-0.93). Studies in Loblolly pine (Sprague *et al.* 1983) reported individual heritability of Pilodyn penetration of 0.46 and genetic correlation with density of -0.82.

The lower heritability for Pilodyn penetration when based upon eight observations per tree taken across four aspects compared with the heritability based upon only two observations on any single aspect may be explained by the presence of tree-by-aspect interaction with Pilodyn penetration. This was investigated by examining the genetic correlation between Pilodyn observations made on different aspects (Table 5.5). Genetic correlations between aspects are consistently lower than unity, and as a consequence, aggregating Pilodyn observations made on different aspects would result in a reduction in individual (observation) heritability compared with estimates based upon observations made on a single aspect.

Table 5.5: Genetic correlation between Pilodyn observations made on different aspects (based upon 2 observations per aspect).

r_g	North	West	South
West	0.76		
South	0.74	0.72	
East	0.78	0.76	0.76

5.3.2 *Repeatability of Pilodyn observations*

Even if measurements are taken on a single aspect, improvement in selection can be made by taking repeated Pilodyn observations. Repeatability (ρ) provides a measure of the effect of repeated observations of a trait on the accuracy of selection of that trait. In the case of Pilodyn penetration, the repeatability was calculated to be 0.90. This high value indicates that most of the observed variation is found between trees and as a consequence only a few observations are required for a reliable estimation of a tree's value. The theoretical accuracy of phenotypic selection for a given number of observations per tree can be calculated using selection theory (e.g. Nicholas 1987) and is illustrated in Figure 5.2. It should be noted that since the genetic correlation between Pilodyn observations made on different aspects was lower than unity, the heritability used in the calculation of accuracy must be that observed for observations made at a single aspect (i.e. h^2=0.60, Table 5.4). Thus the expressed accuracy of phenotypic selection illustrated in Figure 5.2 (against varying number of Pilodyn observations) refers to observations made on a single aspect.

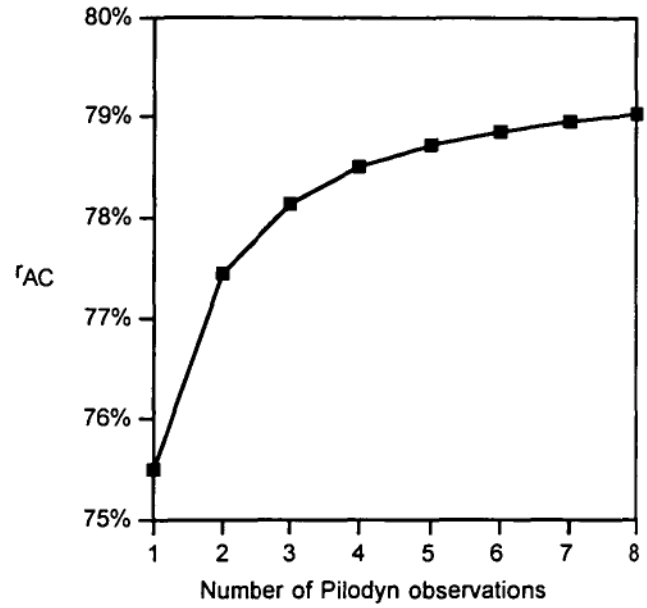

Figure 5.2: Accuracy of phenotypic selection versus the number of Pilodyn observations per tree (on a single aspect). Accuracies were calculated as $r_{AC}=h\sqrt{[m/(1+(m-1)\rho)]}$ and m is the number of measurements per tree, h is the square root of heritability of Pilodyn ($h^2=0.60$) and ρ is the repeatability (after Nicholas 1987).

There is little improvement in accuracy of selection when more than two measurements are made on each tree, due to the high heritability and repeatability observed for Pilodyn. Two observations result in an increase in selection accuracy over a single observation of 2%, and three observations in a further increase in accuracy of less than 1% (Figure 5.2). Two observations per tree provide 98% of the maximum obtainable accuracy.

The number of Pilodyn measurements taken per tree is of practical importance because a large section of bark must be removed for each measurement. In young trees, this might represent a significant portion of the tree circumference, and even with great care and replacement of the removed bark, the damage would be expected to reduce subsequent growth significantly. Micko *et al.* (1982) examined the usefulness of Pilodyn sampling through the bark of white spruce but observed the correlation with density was lower than for under-bark readings. Dean *et al.* (1990) reported bark mass to be highly heritable but only moderately correlated with density for *E. globulus*, thus we would expect Pilodyn penetration through the bark to be more poorly correlated with density

than penetration directly into the wood. Pilodyn sampling involving eight observations (across several aspects), whilst of academic interest, is not suitable for operational tree-selection programs unless sample trees are being destructively sampled for other reasons. Results in this study clearly indicate that there is little to gain in accuracy of selection from taking more than two measurements from a single aspect.

Given that the most efficient Pilodyn sampling method involves two Pilodyn observations on a single aspect, the question of the most appropriate aspect to sample warrants consideration. Table 5.6 presents the individual tree heritability of the mean of two Pilodyn observations per tree (h^2_t) and correlations with 1.3 m whole-disk density, by aspect. Heritability of two Pilodyn observations (h^2_t) is higher for observations on the west and north aspects. G.H. Dean (personal communication[1]) similarly observed the heritability of Pilodyn penetration to be highest on the west aspect of an *E. globulus* trial growing in North-east Tasmania, Australia, with the genetic correlation between Pilodyn penetration and density being highest on the west and north aspects. Expected gain in density from phenotypic selection with Pilodyn (based upon two observations on a single aspect) is directly proportional to $-h_t.r_g$ (Falconer 1989) where h_t is the square-root of the heritability based on the mean of two Pilodyn observations per tree. It is apparent that the west aspect shows the highest value of $-h_t.r_g$ (Table 5.6).

Predominant wind direction in eastern Victoria is from the west, and trees subjected to predominantly westerly wind would be expected to develop higher density tension-wood on the west aspect. Whilst no systematic eccentricity classically associated with formation of tension-wood was observed, Pilodyn penetration is lowest on the western aspect (Table 5.6) indicating a higher density on this aspect. It seems reasonable to assume this phenomena may be due to a greater concentration of tension-wood cells on the western side of the stem. However, whilst aspect shows a significant effect on Pilodyn penetration ($p_{no\text{-}effect}<0.0001$) differences in Pilodyn between the west and east aspect are not significant (for the calculated LSD at $p_{no\text{-}difference}=0.05$ - Table 5.6).

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[1] North Forest Products, Tasmania, Australia

Table 5.6: Mean Pilodyn penetration, heritability for two Pilodyn observations per tree (h^2_t), and the phenotypic (r_p) and genetic (r_g) correlation with density, by aspect. Letters show non-significant differences ($LSD_{(5\%)}$ = 0.095). Expected gain in density from indirect selection via Pilodyn is directly proportional to $-h_t.r_g$ (for phenotypic selection) where h is the square-root of h^2_t.

Aspect	Mean penetration (mm)		h^2_t (r=0.4)	r_p density	r_g density	$-h_t.r_g$
North	10.68	a	0.63	-0.59	-0.93	0.74
South	10.60	ab	0.56	-0.59	-0.91	0.68
East	10.52	bc	0.57	-0.57	-0.89	0.67
West	10.48	c	0.62	-0.61	-0.96	0.76

5.3.3 Expected gain from selection

With a selection intensity of 1% (i=2.665), relative gains in density from phenotypic selection on Pilodyn were 11%, compared with a 13% gain when selecting directly for density. Corresponding gains from index selection (combining individual and family-mean information) for Pilodyn and density were 16% and 19% respectively. The efficiency of using Pilodyn as a means of indirect selection for improving density (assuming two measurements on the west aspect) was therefore 84%. Differences in gains between phenotypic and index selection were relatively small because of the high heritabilities and correlations of both traits.

Whilst expected gain in density from indirect Pilodyn-based index selection is only 84% of expected gain from direct index selection on density, other considerations can affect the efficiency of selection. Firstly, the relative costs of the two methods of sampling are very different. Extracting a disk from breast-height and measuring its density using the moisture displacement method costs an estimated 13.5 times as much (in human resources) as does sampling using a Pilodyn (assuming two Pilodyn observations are made from a single aspect). Figure 5.3 presents the cost of assessment of density on disks and Pilodyn versus the gains in density from selecting the best 20 trees from an assumed total population of 10,000 trees. For a fixed cost figure (vertical axis - Figure 5.3), higher

gains are achieved by selecting on Pilodyn because more trees can be assessed, increasing the selection intensity and thus gain when selecting the required 20 trees. A maximum possible gain from Pilodyn selection of 19% is achieved when all the 10,000 trees are measured, which corresponds to a selection intensity of 0.2%. Although the maximum possible gain in density from Pilodyn selection is 2% lower than the maximum possible gains from direct density selection (around 21%), a given level of gain is achieved using Pilodyn selection at less than half the cost of direct density selection.

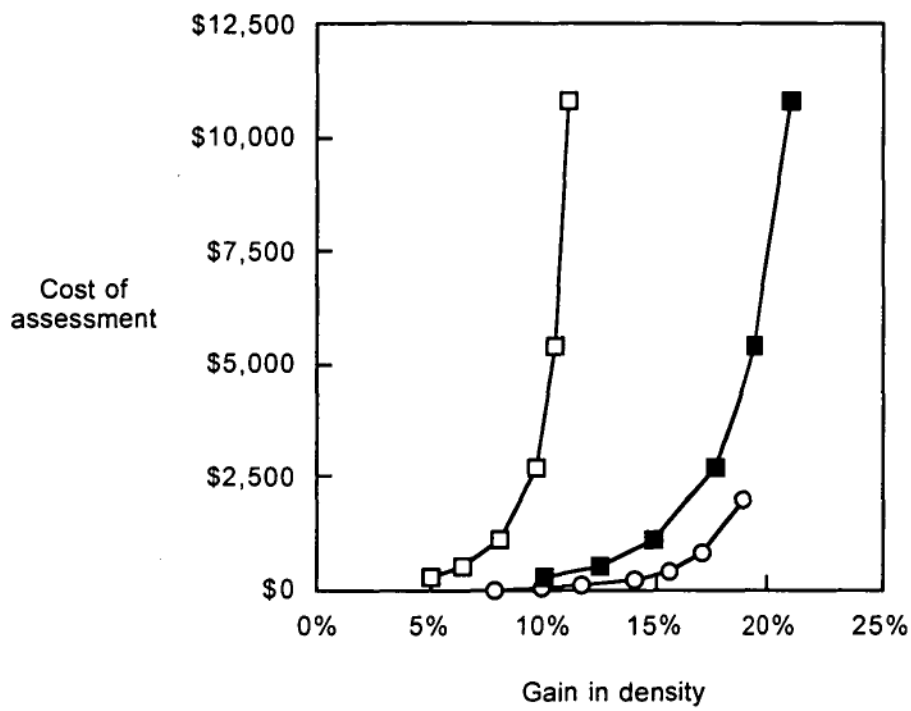

Figure 5.3: Cost of assessment ($AUS) in selection for density versus expected gains (assuming 20 trees are to be selected from a total base population of 10,000 trees) based upon: direct non-destructive density index selection (■); destructive density assessment with family selection on retained trees (□); and indirect Pilodyn index selection (○).

On the other hand, the cost effectiveness of Pilodyn selection for density over direct methods of density determination depends upon the present value of future gains from deployment of improved trees. The greater gain in density achievable using direct assessment may justify the considerably greater immediate cost of direct density assessment in a large deployment program where the benefits may outweigh the cost per deployed tree.

An important consideration is that maximum gains for direct selection for density can only be achieved if sampled trees are not destroyed as a result of assessment. Many *Eucalyptus* species are able to regenerate via coppice growth from a cut stump, thus not precluding the later use of individual destructively-sampled trees for breeding and deployment. *E. nitens* however, rarely regenerates via coppice from a cut stump, so whole-disk sampling in this species would effectively remove each sampled individual from the population unless cuttings or pollen could be taken from each tree prior to sampling (further adding to the cost of selection). If sampled trees are destroyed, the density information can only be used to make selections at a family level resulting in lower gains (from reduced selection intensity) and a much higher cost of achievable gain (Figure 5.3).

Assessment of density via extraction of cores is a possible alternative to Pilodyn for estimation of density in standing trees. Whilst such a method is currently very difficult due to the toughness of eucalypt wood, it has the advantage that all growth rings are sampled relatively non-destructively. The cost of density assessment via increment core would probably be similar to the cost of whole-disk density assessment (Gough and Barnes 1984) thus not negating the savings possible with Pilodyn assessment.

Finally, selection of sampled families on the basis of growth rate would have resulted in reduced additive variance for growth in the selected population, with the magnitude of the reduction defined by the accuracy of selection (heritability). The variance of traits showing correlation with growth would have also been reduced in the selected population, with the magnitude of reduction defined by the degree of correlation between growth and the correlated traits (Villanueva and Kennedy 1990). Whilst the relevance of these effects cannot be defined from the results presented here, the heritability for growth in temperate eucalypts may be low (e.g. h^2 of 0.18 reported by Dean *et al.* 1990), and the relationship between growth and density also low (r_g of -0.22, Dean *et al.* 1990). As more than 50% of families were sampled, the effect on results presented here is assumed to be small, and influence on conclusions negligible.

5.4 CONCLUSION

Individual Pilodyn penetration and 1.3 m disk density showed relatively high heritabilities of 0.60 and 0.73 respectively. The heritability of Pilodyn penetration and its correlation with density was aspect dependent. The repeatability of Pilodyn observations was very high (0.90) and two observations per tree were sufficient for indirect density selection (providing 94% of the maximum possible selection accuracy for multiple observations). Two Pilodyn observations on the west aspect (the aspect shown to be most favourable in this study) gave a heritability of 0.62, a genetic correlation with density of -0.96, and an efficiency of indirect selection of 84%.

Whilst Pilodyn assessment of density will not yield as much gain in density as direct density selection, Pilodyn assessment is considerably cheaper and a much higher selection intensity can be achieved with Pilodyn selection for a given cost of assessment. Thus the expected gain in density per dollar spent on assessment is higher for Pilodyn selection. The destructiveness of direct density assessment may preclude individual selection in which case gains achievable from Pilodyn far exceed expected gains from direct assessment.

5.5 ACKNOWLEDGMENT

Dr. Alan Farrington of Amcor Research & Technology performed the assessment of the family *"whole-tree"* density (section 5.2.4).

Chapter 6:

Genetic control and repeatability of near infrared reflectance from *Eucalyptus nitens* woodmeal

This chapter has been published as:

Greaves, B.L., Schimleck, L., Borralho, N.M.G., Michell, A.J. and Raymond, C.A. 1996. Genetic control and repeatability of near infrared reflectance from *Eucalyptus nitens* ground wood. *Appita Journal* **49**: 423-426.

6.1 INTRODUCTION

Analysis of near infrared reflectance (NIR) spectra of woodmeals has been shown to have application in the indirect assessment of wood-traits of commercial importance to chemical pulping such as pulp yield and the total alkali required for the pulp to reach a given Kappa number (Wright *et al.* 1990, Woitkovich *et al.* 1994, Michell 1995).

Heritability describes the degree of observed variation in a biological *"trait"* (e.g pulp yield) which can be attributed to expressed genetic variation. Heritability can range from 1, meaning that all observed variation is due to heritable genetic variation, to 0, meaning that none of the observed variation is due to heritable genetic differences. Previously reported heritabilities[1] of pulp yield in eucalypts range from 0.19 (*E. globulus*, Borralho *et al.* 1993) to 0.34 (*E. globulus*, Dean *et al.* 1990).

Repeatability, the ratio of the variation between repeated measurements and the total observed variation, is a measure of the agreement between

[1] Values have been adjusted for a coefficient of relationship of 0.4 after Volker *et al.* (1990)

repeated observations of the same trait (Falconer 1989). The theoretical maximum repeatability is 1, indicating that repeated observations (of the same trait) will be identical. Repeatability lower than 1 indicates that there are differences between repeated observations of the same trait, and as differences between repeated observations increase, the repeatability declines. Repeatability can be used to calculate the number of repeated observations that are required to achieve a given accuracy of prediction.

A preliminary step in the evaluation of NIR analysis for the genetic improvement of related commercial traits is (i) the determination of the degree to which NIR is under genetic control (heritability) and (ii) the agreement (repeatability) between multiple observations from the same sample. In this study, the heritability and repeatability of NIR (over the range 1100 - 2500 nm) were determined from spectra collected from small wood samples taken from the outer-most growth-rings of 588 seven-year-old plantation-grown *Eucalyptus nitens* trees.

6.2 METHOD

6.2.1 Trial sites

Five hundred and eighty-eight seven-year-old *E. nitens* trees were sampled from a progeny trial established by Australian Paper Plantations Pty. Ltd. on two contrasting sites in eastern Victoria, Australia (Table 6.1). Trees were nursery raised in containers, and established using operational practices in July 1986 at a planting density of 1000 stems per hectare (Bennett *et al.* 1989).

Table 6.1: Description of trial sites, site preparation and fertiliser treatment at establishment.

	Site 1	Site 2
Soil	gradational clay-loam	duplex: sandy loam over clay
Latitude (°S)	38	38
Longitude (°E)	146	147
Altitude (m a.s.l.)	200	80
Rainfall (mm yr^{-1})	1006	728
Previous landuse	Radiata pine plantation	agricultural pasture
Site preparation	winged rip, disc plough	ridge plough
Fertiliser at planting (kg ha^{-1})	N 4.2, P 0.9, K 0.9	N 4.2, P 50.9, K 50.9

6.2.2 Field design

Both trial sites were established as 40 randomised complete blocks, each composed of 104 single-tree plots (including 94 trial families and 10 *"control"* commercial seedlots), giving a total of 40 trees per family per site. Sample trees were primarily taken from six blocks on each site.

6.2.3 Genetic material

The 94 open-pollinated families included in the trial are from six collection areas (Table 6.2), five of the Toorongo provenance and one of the Rubicon provenance, as classified by Pederick (Pederick 1979). Provenances were included in the trial on the basis of previously reported growth and tree-form (Pederick 1986). Of the 94 families, the 50 families with the greatest diameter at age seven were sampled.

Table 6.2: Seed origin of the genetic material in the sampled progeny trial. "Families in top 50" shows the number of families from each collection area which were sampled for Pilodyn and wood-property traits.

Collection area	Provenance	Latitude (°S)	Longitude (°E)	Altitude (m a.s.l.)	Rainfall (mm p.a.)	Families in trial	Families in top 50
1	Toorongo	38	146	1240	1400	20	5
2	Rubicon	37	144	1000	1200	8	4
3	Toorongo	38	146	800	1400	5	2
4	Toorongo	38	146	1200	1400	24	16
5	Toorongo	38	146	400	1400	19	9
6	Toorongo	38	146	800	1400	18	14

6.2.4 Sampling

The outer-most growth-ring of each tree was sampled at two points on opposite sides of the stem at a height of 15% of total tree height (approximately 2.5 m from the ground). The two outer-ring samples were combined to a single sample for each tree for NIR analysis. Samples were allowed to dry slowly in air before being reduced to meal by milling in a Wiley Mill No. 4 according to AS1301 002s-91 (Anon. 1995). The woodmeal was mixed and two 1.5 g (replicate) samples were taken for NIR analysis (making a total of 1176 samples: 588 trees by two replicate samples per tree).

6.2.5 NIR analysis

The NIR spectra were measured as diffuse reflection from the woodmeal samples contained in micro-sample cups in a spinning holder using a NIRSystems Inc. Model 5000 scanning spectrophotometer with a ceramic standard as reference. Reflectance was measured at 2 nm intervals over the range 1100 - 2500 nm and a total of 50 scans were accumulated for each sample and their scans were averaged by the Model 5000 software to produce one reflectance spectrum per sample (i.e. a total of 1176 spectra: one spectrum from each of two replicate samples per tree, by 588 trees). The spectra were converted to the second derivative mode using the instrument's software with a segment of 10 nm and a gap of 20 nm. The

second derivative mode was used to minimise the effects on the reflectance spectrum of differences in particle size and to give improved band resolution (Barton 1989).

6.2.6 Statistical analysis

Variance components were estimated for each band in the spectrum using the model (in matrix notation):

[6.1] $$\mathbf{y} = \mathbf{Xb} + \mathbf{Z}_1\mathbf{f} + \mathbf{Z}_2\mathbf{i} + \mathbf{Z}_3\mathbf{t} + \mathbf{e}$$

where **y** is a vector of observations (the second derivative of observed reflectance), **b** is a vector of fixed effects (site, replicates within site and seed collection area), **f** is a vector of family effects (random effects), **i** is a vector of family-by-site interaction effects (random effects), **t** is a vector of effects due to trees within families (random effects), **e** is the vector of residuals (within tree effects) and **X**, $\mathbf{Z}_1$, $\mathbf{Z}_2$ and $\mathbf{Z}_3$ are incidence matrices relating observations to the effects in the model.

The variance components for the random terms (Eqn. 6.1) were estimated using the SAS MIXED-REML procedure (SAS Institute Inc. 1992).

Heritability (h^2) was calculated after:

[6.2] $$h^2 = \frac{\sigma_f^2}{r.\left(\sigma_f^2 + \sigma_i^2 + \sigma_t^2\right)}$$

where σ^2_f is the between-family variance; σ^2_i is the variance of family-by-site interaction; σ^2_t is the between-tree (within-family) variance; and r is the coefficient of relationship (assumed to be 0.4 after Volker *et al.* 1990).

Standard error for heritability (*S.E.*) was determined as (Becker 1984):

[6.3] $$S.E. = \frac{1}{r}.\sqrt{\frac{2.(n-1).(1-t)^2.\left[1+(k-1).t\right]^2}{k^2.(n-S).(S-1)}}$$

where n is the number of trees (n=588); k is the harmonic mean of the number of observations per family (k=23.3); S is the number of families (S=50); and t is the interclass correlation calculated after:

$$[6.4] \quad t = \frac{\sigma_f^2}{\sigma_f^2 + \sigma_i^2 + \sigma_t^2}$$

Repeatability (ρ) was calculated after:

$$[6.5] \quad \rho = \frac{\left(\sigma_f^2 + \sigma_i^2 + \sigma_t^2\right)}{\left(\sigma_f^2 + \sigma_t^2 + \sigma_i^2 + \sigma_e^2\right)}$$

where σ^2_e is the between-sample variance (i.e. the variation between the two replicate observations per tree).

The level of family by site interaction was expressed as i^2, defined here as ratio of the family-by-site interaction variance (σ^2_i) to the total variance between trees:

$$[6.6] \quad i^2 = \frac{\sigma_i^2}{\left(\sigma_f^2 + \sigma_i^2 + \sigma_t^2\right)}$$

Heritability, standard error for heritability, family-by-site interaction, repeatability, and the effects of site (fixed effects) were estimated for the second derivative value of the observed reflectance for each of the 700 (2 nm wide) bands. A ten band (20 nm wide) moving average was calculated for each parameter to reduce random variability.

6.3 RESULTS AND DISCUSSION

Individual heritability for (the second derivative of) observed reflectance ranged from 0 to 0.62 (0 to 0.35 for the 10 band moving average). Standard error for heritability ranged from 0.02 to 0.11 (0.02 to 0.08 for the 10 band moving average). Repeatability ranged from 0.05 to 0.99 (0.15 to 0.99 for the 10 band moving average). The observed repeatability, heritability (and standard error of heritability) across the near infrared region from 1100 to 2500 nm is presented in Figure 6.1.

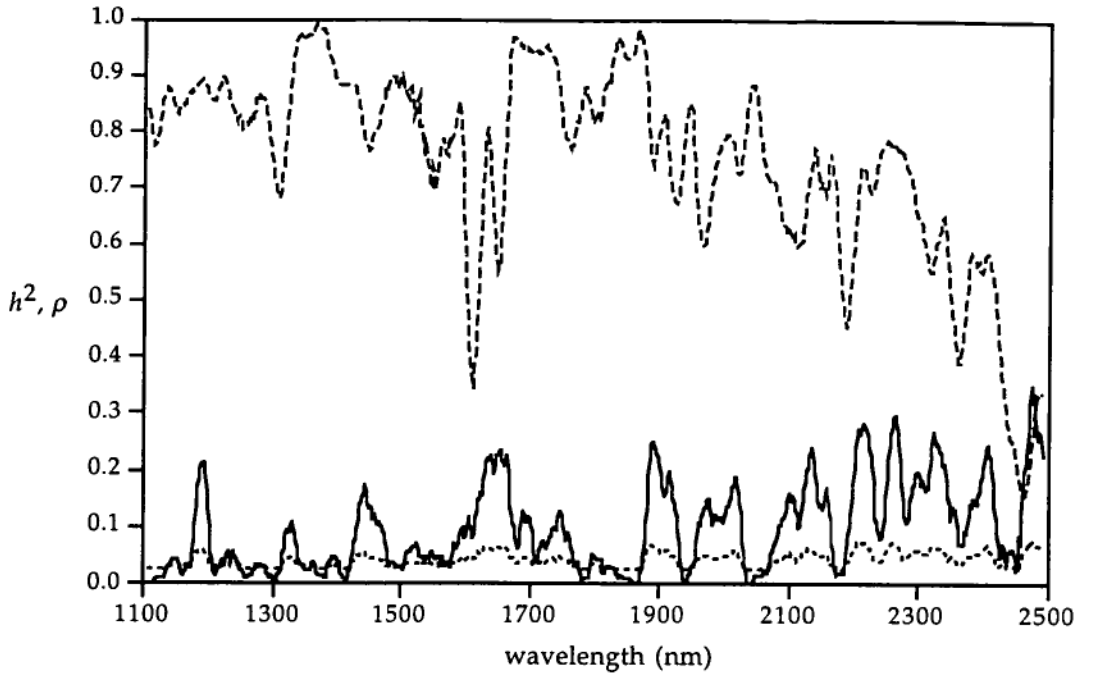

Figure 6.1: Repeatability (ρ: - - - -), heritability (h^2: ——) and standard error of heritability (.....) for the second derivative of observed reflectance versus wavelength. Each presented observation represents a moving average of 10 2 nm wide observations.

Bands in the NIR spectra of woods are less readily related to particular chemical components of wood than bands in their mid infrared (MIR) spectra (Barton 1989). However, assignments with chemical bond types can be made in a general sense for particular regions of the NIR spectrum as shown in Table 6.3.

Table 6.3: Assignments of bands in the region 2500 - 1100 nm of the NIR spectrum (from literature supplied by NIRSystems Inc.)

Region (nm)	Assignment
1100 - 1230	2nd overtone of C-H stretch vibrations
1375 - 1770	1st overtone of C-H, N-H and O-H stretch vibrations and of C-H combinations
1875 - 1975	2nd overtone of C=O stretch vibration
1900 - 2500	combinations of C-C, C-H, N-H and O-H stretch vibrations

The numerous overlapping bands in these regions (Table 6.3) make detailed band assignment very difficult. There are, however, a few bands which alone absorb at particular wavelengths and more detailed band assignment is sometimes possible. In addition it has been noted that the absorbance of some bands changes when the wood is pre-treated with chemicals such as alkali. The results of such studies of the bands in the NIR spectra of eucalypts have been reported (Michell and Schimleck 1996). Examples of bands that have been assigned to specific wood components (Michell and Schimleck 1996) include 1666 nm and 2132 nm for lignin, which both appear as significant heritability peaks (h^2 0.23 and 0.24 repectively - Fig. 6.1), and 1484 and 2100 nm for cellulose (although only 2100 nm shows a significant heritability peak, reaching 0.17).

Since the NIR spectra reflect the chemistry of the woods, the heritability of the NIR reflectance might be expected to mirror the heritability of the chemical composition of the woods. The low to moderate heritability ($\approx$ 0.2) of particular regions of the reflectance spectra suggests that, should these regions show correlation with commercial traits such as pulp yield and total alkali demand, analysis of near infrared reflectance may prove to be a moderately effective method for screening large numbers of trees for these traits. If the method is to be applied to breeding, it may be appropriate to exclude spectral regions of low heritability from analysis.

The regions of the reflectance spectra which show low heritability, however, may still show correlation with traits of commercial interest such as pulp yield. Whilst excluding regions of low heritability may improve the accuracy of selecting for genetic differences in tree breeding programs, for general wood-property assessment analysis of the full spectra may be more appropriate. For example, trees of common genetic origin which have been treated with differing fertiliser regimes to assess the impact of these regimes on wood properties may express differences in the regions of the NIR spectrum where heritability is low.

Repeatability appears to be relatively high (0.7 - 1.0) and stable for wavelengths shorter than 2300 nm but for two major depressions at 1613 and 1650 nm and some weaker depressions near 1900, 2100 and 2180 nm (Fig. 6.1). However, repeatability shows a steady decline from near 1.0 at 1850 nm to 0.7 at 2250 nm and to a low 0.3 at 2500 nm. The region from 2250 to 2500 nm is one in which the bands are likely to be affected by variable scattering from the samples (Osborne *et al.* 1993). Variation in

scattering may be due to variation in particle size (resulting from different responses of wood samples to milling), or to random differences in the packing of the woodmeal samples for scanning. However, whilst the 2250 - 2500 nm region shows a number of moderate heritability peaks (Fig. 6.1) it has so far not featured prominently in models relating pulpwood traits of commercial importance to the spectra (Michell 1995) and might well be omitted in predictions of these traits. Should further analysis show the region above 2250 nm to be important, the number of repeated observations per sample will need to be increased to maintain accuracy of prediction in light of the declining repeatability in this region.

Family-by-site interaction is an important consideration in breeding. A high level of interaction implies that genetic worth is expressed differently on different sites - i.e. that relative genetic worth differs across sites, or that the ranking of genetic worth changes from one site to the next. When selecting trees in breeding programs, consideration must be given to the interaction between genetic performance and site as across-site performance may be more important than performance on a particular site. Figure 6.2 demonstrates that whilst some bands show considerable family-by-site interaction (i^2) those bands where reflectance is under stronger genetic control (h^2) show low interaction. Since a breeder would preferentially use bands which show a high heritability, family-by-site interaction may not be an issue if Near Infrared Reflectance is used for breeding.

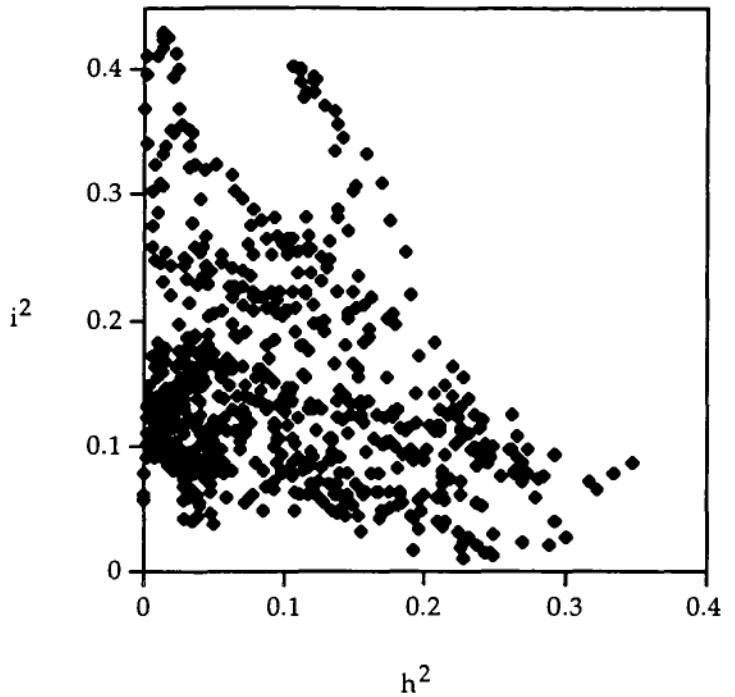

Figure 6.2: Relationship between the degree of family-by-site interaction (i^2 - after Eqn. 6.6) and heritability (h^2 - after Eqn. 6.2). Each presented observation represents a moving average of 10 x 2 nm wide observations.

The magnitudes of the (fixed) site effects were examined across the 700 bands to determine if differences exist between (second derivative of) the observed reflectance. Whilst some bands showed a significant difference between the two sites there were no obvious trends in site differences across the spectrum. Generally the observed responses were consistent across the two sites.

Finally, selection of sampled families on the basis of growth rate would have resulted in reduced additive variance for growth in the selected population, with the magnitude of the reduction defined by the accuracy of selection (heritability). The variance of traits showing correlation with growth would have also been reduced in the selected population, with the magnitude of reduction defined by the degree of correlation between growth and the correlated traits (Villanueva and Kennedy 1990). Whilst the relevance of these effects cannot be defined from the results presented here, the heritability for growth in temperate eucalypts may be low (e.g. h^2 of 0.2 reported by Dean *et al.* 1990), and the relationship between growth and pulp yield moderate (r_g of -0.4, Dean *et al.* 1990). As more

than 50% of families were sampled, the effect on results presented here is assumed to be small, and influence on conclusions negligible.

6.4 CONCLUSION

Near infrared reflectance spectra (1100 - 2500 nm, in 700 discrete 2 nm bands) were captured (as the second derivative of the reflectance spectra) from woodmeal sampled from the outer growth-rings of 588 7-year-old plantation-grown *E. nitens* trees. Heritability of reflectance across the spectra ranged from 0 to 0.35 (for a 10 band moving average). Repeatability of observed reflectance was consistently greater than 0.7 for wavelengths shorter than 2250 nm, but showed decline at longer wavelengths to a low 0.3 at 2500 nm. Bands showing high heritability showed low family-by-site interaction.

6.5 ACKNOWLEDGMENT

Laurie Schimleck of the Cooperative Research Centre for Hardwood Fibre and Paper Science performed the NIR analysis (section 6.2.5), using techniques he developed whilst working towards his PhD (Schimleck 1996) under the supervision of Dr Anthony Michell.

Chapter 7:

Age-age correlations in, and relationships between basic density and growth in *Eucalyptus nitens*

This chapter has been submitted to *Silvae Genetica* and is currently in review:

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7.1 INTRODUCTION

Knowledge of the changes in heritability of traits, and correlations between these traits assessed at different ages, are necessary for determination of efficiencies of early selection (Kang 1985).

Determining trends in heritability and age-age correlations is relatively simple for growth traits, requiring only patience and repeated assessment. Whilst there are many reported age-age correlations for growth in conifers (e.g. Lambeth 1980, McKeand 1988, Riemenschneider 1988, King and Burdon 1991, Matheson *et al.* 1994) there are few in eucalypts (Van Wyk 1990, Borralho *et al.* 1992a).

Methods for assessing density (the dry mass of wood per unit of green or dry volume), on the other hand, range from invasive for assessment via Pilodyn (Chapter 5) or cores, to destructive for assessment via disks or chips, and reliable repeated measurement is not feasible. As an approximation, cores or disks can be sampled at a later-age and, by determining the density of individual growth-rings, inferences can be made regarding density at earlier ages (e.g. Loo *et al.* 1984, Robinson 1984, Robinson and Mize 1987, Gonzalez and Richards 1988, Vargas-Hernandez and Adams 1992) and age-age correlations determined. There are, however, no reported genetic age-age correlations for density in plantation eucalypts.

Lambeth (1980) demonstrated that age-age correlations for growth in a number of coniferous species showed a strong linear relationship with the log of the ratio of the ages (*LAR*), that the relationship was robust across species and growing environments, but that the relationship broke down where the early age measurement was made at one year after planting. Kang (1985) further refined Lambeth's (1980) relationship, concluding that selection ages of less than one third of rotation age should be used with caution. McKeand (1988) and Riemenschneider (1988) applied Lambeth's (1980) relationship to early selection for growth in Loblolly pine and Jack pine respectively, whilst Matheson *et al.* (1994) found the relationship did not fit observed age-age correlations for growth in 14 year-old Radiata pine.

Negative genetic relationships between density and diameter are commonly reported for conifers (e.g. Dean *et al.* 1983, Loo *et al.* 1984, Vargas-Hernandez and Adams 1991), and the few reported genetic correlations in eucalypts also indicate a negative relationship (Malan 1988, Dean *et al.* 1990, Borralho *et al.* 1992c).

This chapter will investigate trends in heritability and age-to-age correlations of density through examination of pith-to-bark density measurements made on cores cut from 588 seven-year-old plantation-grown *Eucalyptus nitens* trees. Three growth measurements, height at 20 months and diameter at 1.3 m at four and seven years, assessed over a larger sample of families but including the sampled trees, will be used to make similar inferences for growth.

7.2 METHODS

7.2.1 Measurements

Total height at 20 months (*HT20M*) and over-bark diameter at 1.3 m at ages four and seven years (*DBH4* and *DBH7*) were assessed on 1316 trees from 94 open-pollinated families established under operational conditions on two contrasting sites (Table 7.1) in south-eastern Victoria, Australia (2 sites by 7 randomised complete blocks per site by 94 open-pollinated families per block). Five hundred and eighty-eight trees from the 50 families with the greatest mean diameter were sampled for Pilodyn penetration

(2 penetrations per tree at 1.3 m on the west aspect, after Chapter 5) before being felled for density sampling (2 sites by 50 families by 6 trees per family per site, excluding missing trees). Each felled tree was measured (diameter at 1.3 m, diameter at 15% and 35% of total height, height to 5.5 cm over-bark diameter, and total height), and the measurements used for estimation of total stem volume.

Table 7.1: Description of trial sites (after Bennett *et al.* 1989).

	Site 1	Site 2
Soil	gradational clay-loam	duplex: sandy loam over clay
Latitude (°S)	38	38
Longitude (°E)	146	147
Altitude (m a.s.l.)	200	80
Rainfall (mm yr^{-1})	1006	728
Previous landuse	Radiata pine plantation	agricultural pasture
Site preparation	winged rip, disc plough	ridge plough
Fertiliser at planting (kg ha^{-1})	N 4.2, P 0.9, K 0.9	N 4.2, P 50.9, K 50.9

Ten centimetre thick disks were cut from each tree from a fixed height of 1.3 metres and from 15% of total tree height (approximately 2.5 m). Each disk was sealed in plastic to minimise desiccation, and stored frozen (at -18°C) until analysis. Wood densities for the disks from 1.3 m were determined using the water displacement method T258 om-89 (TAPPI 1989).

Radial strips of approximately 15 mm tangential width were cut from the frozen 15% height disks, exchanged with ethanol over a period of weeks, and dried from absolute ethanol at room temperature and under reduced pressure to avoid collapse. The strips were reduced on an automated twin-blade saw to 2 mm (tangentially) by 6 mm (longitudinally) and conditioned at 45% relative humidity and 20°C.

Density profiles were determined at a radial resolution of 50 µm using the x-ray densitometric facility in SilviScan-1 (see Evans *et al.* 1995 for a detailed description of the SilviScan density assessment technique). Cu K_a radiation from a fine focus tube was collimated to 50 µm horizontally by 200 µm vertically at the sample and reflected from a flat graphite monochrometer into a scintillation detector. The photon count rate in air was approximately

25000 sec^{-1}. 2500 photons were counted at each position, with a standard deviation of approximately 2%, in accordance with Poisson statistics. Mass attenuation coefficient was assumed to be constant within each sample. Each density profile was normalised by the average density determined independently from the sample mass and volume, as measured by micrometry. The standard deviation of sample thickness, which contributes in direct proportion to errors in the estimated density profiles, was less than 1%.

Custom written software (Evans 1993) was used to determine the average density of individual annual growth rings and earlywood and latewood components.

Density measured using the water displacement method (1.3 m disks) is basic density, defined as the oven-dry weight of wood per unit of green volume, whereas density measured using SilviScan is dry density, defined as the weight of wood per unit of dry volume at approximately 10% moisture content. Whilst the absolute density values determined using these two methods cannot be directly compared, the methods were assumed here to give correlated results.

7.2.2 *Whole-disk and whole-core density aggregates*

Using individual ring earlywood (*EW*) and latewood (*LW*) densities and the thickness of each band, weighted average whole-core (pith to bark) and whole-disk densities for each age were determined after:

$$[7.1] \quad core.dens_i = \frac{\sum_{i}^{n=3}\left(densEW_n.widthEW_n + densLW_n.widthLW_n\right)}{\sum_{i}^{n=3}\left(widthEW_n + widthLW_n\right)}$$

$$[7.2] \quad disk.dens_i = \frac{\sum_{i}^{n=3}\left(densEW_n.areaEW_n + densLW_n.areaLW_n\right)}{\sum_{i}^{n=3}\left(areaEW_n + areaLW_n\right)}$$

where $core.dens_i$ and $disk.dens_i$ are the core density and disk density in the i^{th} year respectively; $densEW_n$ and $densLW_n$ are the earlywood and latewood density of the n^{th} ring respectively; $widthEW_n$ and $widthLW_n$ are the widths

of the earlywood and latewood bands of the n^{th} ring respectively; and $areaEW_n$ and $areaLW_n$ are the areas of the earlywood and latewood bands of the n^{th} ring respectively calculated assuming the disks are circular and the rings concentric.

7.2.3 Statistical analysis

The model used for the multivariate analysis of variance components was, in matrix notation:

$$[7.3] \quad \mathbf{y} = \mathbf{Xb} + \mathbf{Z}_1\mathbf{f} + \mathbf{Z}_2\mathbf{i} + \mathbf{e}$$

where **y** is the vector of observations for one or multiple traits, **b** is the vector of fixed effects (replicates within site and seed collection area), **f** and **i** are vectors of open-pollinated family effects and family-by-site interaction effects respectively, **e** is the vector of residuals and **X**, $\mathbf{Z}_1$ and $\mathbf{Z}_2$ are incidence matrices relating observations to the effects in the model.

The (co)variance structure (V) for the analysis can be described as (after Meyer 1994):

$$V(\mathbf{f}) = \mathbf{G}_f \times \mathbf{I}$$

$$V(\mathbf{i}) = \mathbf{G}_i \times \mathbf{I}$$

$$V(\mathbf{e}) = \mathbf{R} \times \mathbf{I}$$

where: **f** and **i** are vectors of family and family by site effects respectively; **e** is a vector of residual errors; $\mathbf{G}_f$ is the matrix of family variances and covariances amongst traits; $\mathbf{G}_i$ is the matrix of family-by-site covariances; **R** is the matrix of residual covariances; and **I** is the identity matrix. All covariances between effects were assumed to be zero.

Estimates of variance components were calculated using REML VCE software using a quasi-Newton algorithm of variance and covariance (Groeneveld 1995). Individual, across-site narrow-sense heritability (h^2) was calculated after:

$$[7.4] \quad h^2 = \frac{\sigma_f^2}{r.\left(\sigma_f^2 + \sigma_i^2 + \sigma_e^2\right)}$$

where σ^2_f is the between-family variance; σ^2_i is the variance of family by site interaction; σ^2_e is the within-family variance; and r is the coefficient of relationship (assumed to be 0.4 after Volker *et al.* 1990). Standard errors for

heritability, where presented, were determined after the method described by Becker (1984).

7.2.4 Age trends in genetic correlation

An empirical relationship between age-age genetic correlations ($r_{j\text{-}m}$) and the natural log of the age ratio (*LAR*), as proposed by Lambeth (1980), was fitted for each trait:

[7.5] $$r_{j-m} = b(LAR) + c$$

where $$LAR = \log_e\left(\frac{\text{Early Age}}{\text{Later Age}}\right)$$

and c is the intercept (the genetic correlation when $LAR = 0$, theoretically equal to 1).

The goodness of fit of the *LAR* relationships was expressed by the coefficient of determination (r^2).

7.3 RESULTS AND DISCUSSION

7.3.1 Observed trait means

The observed site means of the assessed growth traits and disk density at 1.3 m are presented in Table 7.2.

Table 7.2: Site means for assessed total height at 20 months (*HT20M*), over-bark diameter at 1.3 m at ages four and seven years (*DBH4* and *DBH7*) and 1.3 m disk density.

Trait	SITE 1	SITE 2
HT20M	3.03 m	4.38 m
DBH4	10.3 cm	11.6 cm
DBH7	16.9 cm	16.3 cm
1.3 m disk density	0.471 t m^{-3}	0.541 t m^{-3}

It is apparent that Site 2 provided faster initial growth (*HT20M*), but growth declined in relation to Site 1 with time. By age seven years (*DBH7*) both sites showed similar average annual growth rate. Whole disk density at 1.3 m was considerably higher on Site 2 than Site 1.

Four examples of the SilviScan density traces are presented in Figure 7.1. Ring boundaries, between the older latewood and the more recent earlywood, were relatively simple to locate with consistency on the SilviScan traces. The earlywood-latewood transition boundaries within each ring, however, were more difficult to locate with consistency due to the varying presence of *false* latewood peaks (e.g. Figure 7.1a), and time differences in the commencement of deposition of higher-density latewood between individual trees (e.g. Figures 7.1a and 7.1b).

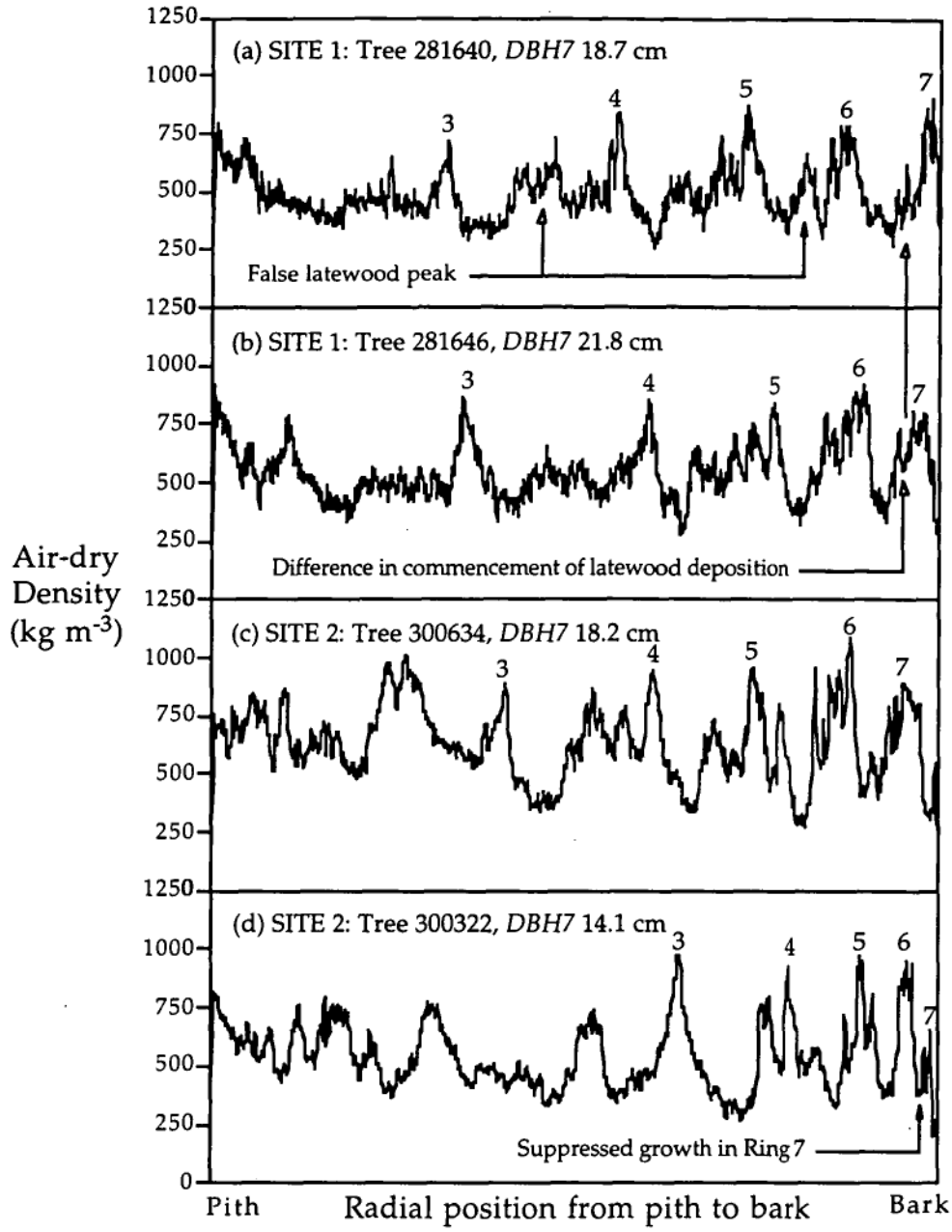

Figure 7.1: Pith to bark density traces produced by the SilviScan instrument (*DBH7* refers to tree diameter over-bark at 1.3 m at age 7); plain numbers indicate tree age when latewood peaks were deposited.

Figures 7.1a and 7.1b depict density profiles from two trees from Site 1, and Figures 7.1c and 7.1d are from Site 2. The two sites were located relatively close together (35 km apart) and both received adequate nutrition, yet the differences in absolute density and density profile between sites is considerable (Table 7.2, Figure 7.1). Whilst it is not possible to determine the cause of the density differences, differences in soil type, previous land-use and micro-climate may have been contributing factors.

Whole-ring density (after SilviScan) increased with age of deposition on each site, whilst maintaining a difference of around 0.08 t m^{-3} between sites (Figure 7.2).

The weighted aggregated density traits, core density and disk density (Eqn. 7.1 and 7.2), similarly increased with age, whilst maintaining the observed site difference (Figure 7.2). The aggregate densities rose more slowly than the individual-ring densities because the lower density inner-rings are always represented in later-age whole-disk or whole-core aggregates. Aggregate disk density weights the outer-wood density more highly than does aggregate core density and thus disk density was consistently greater than core density.

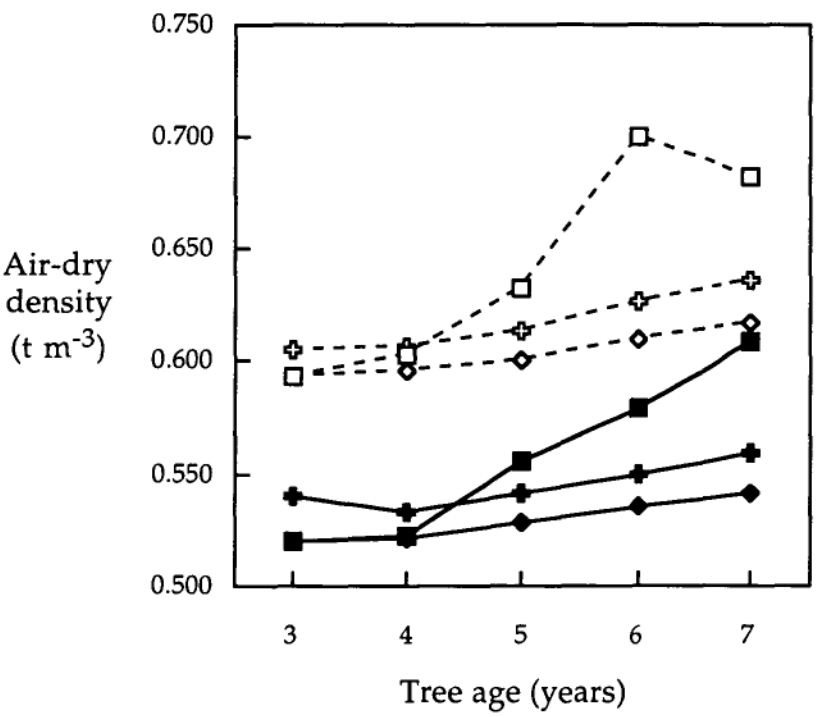

Figure 7.2: Outer-most whole-ring density (Site 1 = ■, Site 2 = □), aggregate whole-disk density (Site 1 = ✚, Site 2 = ✜), and aggregate whole-core density (Site 1 = ◆, Site 2 = ◇) with tree age.

7.3.2 Genetic Parameters

The narrow-sense heritabilities of earlywood, latewood, and whole-ring density, by growth-ring, are presented in Table 7.3. The consistently lower

heritability of both earlywood and latewood in comparison with whole-ring is attributed to the difficulty in partitioning each ring into earlywood and latewood in comparison with the relative ease of separating whole-rings. Incorrect placement of the earlywood/latewood boundary within a ring increases the residual variance of each, thus reducing the apparent heritabilities relative to the whole-ring heritability. Vargas-Hernandez and Adams (1991), working with 15-year-old Douglas fir, similarly observed both earlywood and latewood density to have a lower heritability than whole-ring density.

Table 7.3: Narrow-sense heritability of earlywood, latewood, and whole-ring density, by year of deposition of growth-ring (Ring). Standard errors of heritability are in parenthesis.

Ring	h^2 density		
	Earlywood	Latewood	Whole-ring
3	0.29 (0.09)	0.25 (0.08)	0.31 (0.07)
4	0.27 (0.09)	0.31 (0.10)	0.43 (0.10)
5	0.25 (0.08)	0.27 (0.09)	0.43 (0.11)
6	0.31 (0.09)	0.21 (0.09)	0.44 (0.11)
7	0.09 (0.06)	0.05 (0.05)	0.22 (0.06)

The heritability of individual ring density (Table 7.3) was low in rings three (h^2=0.3) and seven (h^2=0.2) and moderate (h^2=0.4) in rings four, five and six. Whilst each tree was sampled at a fixed proportion of total height, differences in the degree to which the inner-most earlywood is represented in Ring 3 would be dependent upon the relative height of the tree at the earlier age. The varying proportion of earlywood in Ring 3 may be the cause of the higher relative residual variance for this ring and hence the low heritability. The low heritability for Ring 7 resulted from a reduced family variance for this ring associated with an increased error variance. A number of the smaller trees on Site 2 showed signs of being suppressed: Ring 7 was either completely missing or small and of lower density - Figure 7.1(d) depicts the density trace of a smaller tree showing a much reduced Ring 7.

The genetic correlations between earlywood, latewood and whole-ring density were generally very high (Table 7.4) suggesting that these traits are manifestations of the same genes. However, since the heritability of whole-

ring density was consistently higher than the heritability of earlywood or latewood density, further analysis reported in this chapter will concentrate on whole-ring density rather than earlywood or latewood density.

Table 7.4: Genetic correlations between earlywood (*EW*), latewood (*LW*), and whole-ring density, by growth-ring.

correlation	Ring 3	Ring 4	Ring 5	Ring 6	Ring 7
EW - LW	0.65	1.00	0.99	0.98	0.93
EW - whole-ring	1.00	1.00	1.00	1.00	0.93
LW - whole-ring	0.70	0.99	0.99	0.99	1.00

The variance of family-by-site interaction for ring density was consistently low across rings, varying from 0 to 3% of total variance. Similar low genotype-by-environment variation for ring density has been reported in Douglas fir (Yassin Abdel-Gadir *et al.* 1993).

The relationships between growth and density traits measured at age seven years are presented in Table 7.5.

Table 7.5: Relationship between traits at age seven years. Individual across-site heritabilities (diagonal, **bold**), genetic correlations (above diagonal) and phenotypic correlations (below diagonal).

	DBH7	*HT7*	*VOL7*	*PIL*	*RING7*	*CORE7*	*DISK7*	*DENS1.3*
DBH7	**0.42**	0.90	0.99	0.24	-0.48	-0.35	-0.28	-0.20
HT7	0.79	**0.44**	0.92	-0.02	-0.23	-0.09	-0.03	0.09
VOL7	0.96	0.82	**0.46**	0.30	-0.53	-0.40	-0.33	-0.24
PIL	-0.02	-0.14	0.02	**0.59**	-0.97	-0.98	-1.00	-0.98
RING7	-0.15	0.03	-0.15	-0.55	**0.26**	0.98	0.97	0.93
CORE7	-0.09	0.03	-0.11	-0.56	0.63	**0.51**	0.99	0.98
DISK7	-0.07	0.06	-0.09	-0.61	0.72	0.98	**0.53**	0.98
DENS1.3	0.03	0.13	0.00	-0.74	0.52	0.67	0.70	**0.73**

DBH7 and *HT7* are diameter at 1.3 m and total height respectively; *VOL7* is the whole-tree volume calculated from multiple measurements up each tree; *PIL* is the average Pilodyn penetration of two penetrations made under-bark on the west aspect at 1.3 m; *RING7* is the density of the outer-most growth ring at 15% of total tree height (approx. 2.4 m), *CORE7* and *DISK7* are calculated core and whole-disk densities at 15% of tree height; and *DENS1.3* is the measured whole-disk density at 1.3 m.

There were strong genetic relationships (Table 7.5) between *DBH7* and *VOL7* (0.99) and between *HT7* and *VOL7* (0.92). Similar strong relationships between growth traits in plantation eucalypts have been reported by Van Wyk (1990) and Dean *et al.* (1990). Since volume was calculated from measurements of diameter taken along the stem of each tree, there must be some degree of auto-correlation between *DBH7* and volume, particularly since the lower portion of a tree makes a greater contribution towards volume than higher stem sections. However, diameter at a fixed height of 1.3 or 1.4 m is commonly used as a selection trait for total tree volume (Cotterill and Dean 1990) and it is useful to confirm such a high genetic relationship between diameter and total volume in a temperate eucalypt species.

Genetic relationships between the density traits were similarly high (Table 7.5). Pilodyn penetration (at 1.3 m) was highly genetically correlated with ring density (-0.97), and with disk density at both 1.3 m and 15% of tree height (-0.98 and -1.00 respectively). Core and disk density at 15% height were both highly genetically correlated with disk density at 1.3 m (both 0.98), supporting the assumption that estimating density via basic density and dry density methods gives correlated results.

Diameter and density at 1.3 m were weakly and unfavourably correlated at age seven years (r_g = -0.2) confirming genetic relationships reported previously in plantation eucalypts (Malan 1988 r_g = -0.7 (height) and -1.0 (dbh), Dean *et al.* 1990 r_g = -0.4, Borralho *et al.* 1992c r_g = -0.1). The relationship between both *DBH7* and *VOL7*, and density of the outer-most ring (*RING7*), was a moderate -0.5 suggesting that those trees which have shown the highest growth are now producing lower density wood and that the relationship between growth and density may increase (become more negative) with increasing stand age beyond seven years.

The variance of family-by-site interaction was below 3% of the total variance for all traits presented in Table 7.5.

Growth and density traits showed increasing individual heritability with increasing tree age (Figure 7.3), a trend commonly found in short rotation eucalypts (Wei and Borralho 1996).

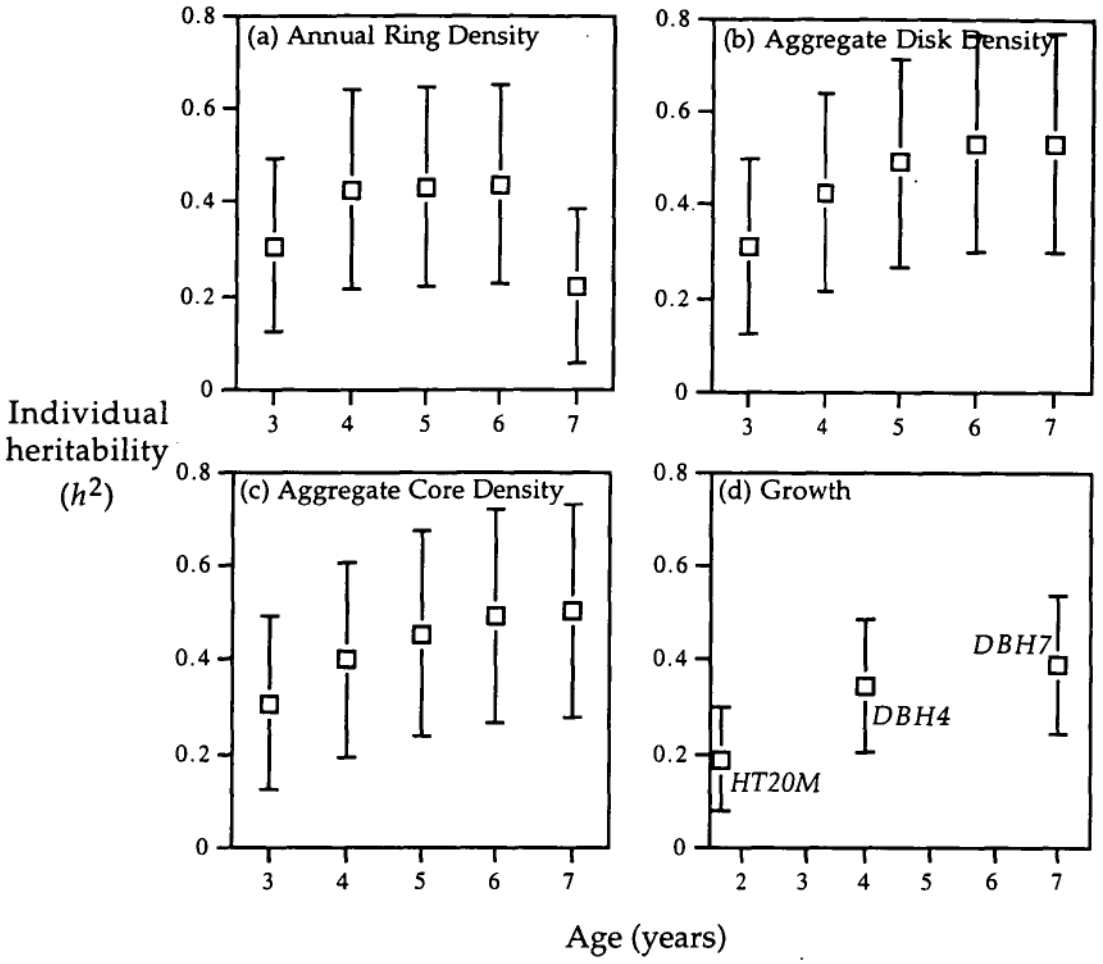

Figure 7.3: Individual heritability (h^2) versus age. Heritability observations for growth (d) are from diameter at 1.3 m (*DBH4*, *DBH7*) and total height (*HT20M*) as indicated. Bars represent 95% confidence limits of prediction.

The observed rise, plateau, and fall in the heritability of individual ring density (Figure 7.3a) may not represent a real trend - all estimates are not significantly different from an average estimate of 0.36.

7.3.3 Age-age correlations

The heritabilities and age-age genetic correlations for: whole-ring densities; disk densities; core densities; and growth traits are presented in Tables 7.6, 7.7, 7.8 and 7.9 respectively.

Table 7.6: Heritabilities (diagonal, **bold**) and genetic correlations (above diagonal) for ring density between ages.

	Ring 7	Ring 6	Ring 5	Ring 4	Ring 3
Ring 7	**0.22**	0.99	1.00	0.98	0.89
Ring 6		**0.44**	1.00	0.95	0.83
Ring 5			**0.43**	0.96	0.86
Ring 4				**0.43**	0.95
Ring 3					**0.31**

Table 7.7: Heritabilities (diagonal, **bold**) and genetic correlations (above diagonal) for disk density between ages.

	Disk 7	Disk 6	Disk 5	Disk 4	Disk 3
Disk 7	**0.53**	1.00	1.00	0.98	0.93
Disk 6		**0.53**	1.00	0.98	0.93
Disk 5			**0.49**	0.99	0.95
Disk 4				**0.43**	0.98
Disk 3					**0.31**

Table 7.8: Heritabilities (diagonal, **bold**) and genetic correlations (above diagonal) for core density between ages.

	Core 7	Core 6	Core 5	Core 4	Core 3
Core 7	**0.50**	1.00	1.00	0.99	0.95
Core 6		**0.49**	1.00	0.99	0.96
Core 5			**0.46**	1.00	0.97
Core 4				**0.40**	0.99
Core 3					**0.31**

Table 7.9: Heritabilities (diagonal, **bold**) and genetic correlations (above diagonal) for growth traits between ages

	DBH7	*DBH4*	*HT20M*
DBH7	**0.42**	0.99	0.52
DBH4		**0.37**	0.49
HT20M			**0.23**

Vargas-Hernandez and Adams (1992) observed genetic correlation between core density at early age (similarly determined as an aggregate of observed individual ring densities) and core density at 15 years rose gradually from around 0.9 at age 7 years to around 1.0 at age 14 years in Douglas fir.

As the core and disk densities are weighted aggregated traits (Eqn.s 7.1 and 7.2) there is a component of auto-correlation when these traits are compared across ages. For example, all of Disk 5 is included in the calculated value for Disk 6 leading to high correlations between these traits. Since later-age core densities are more a function of earlier-age density than are later-age disk densities, the age-age correlations were greater for core density than for disk density. Whilst age-age correlations may be inflated by auto-correlation it is noteworthy that Borralho *et al.* (1992a) observed little difference between genetic parameters for absolute and incremental *growth* traits, suggesting little inflation due to auto-correlation.

The observed correlations (Tables 7.6 - 7.9) are depicted in Figure 7.4 with fitted relationships with the log of the age ratio (*LAR*) as proposed by Lambeth (1980).

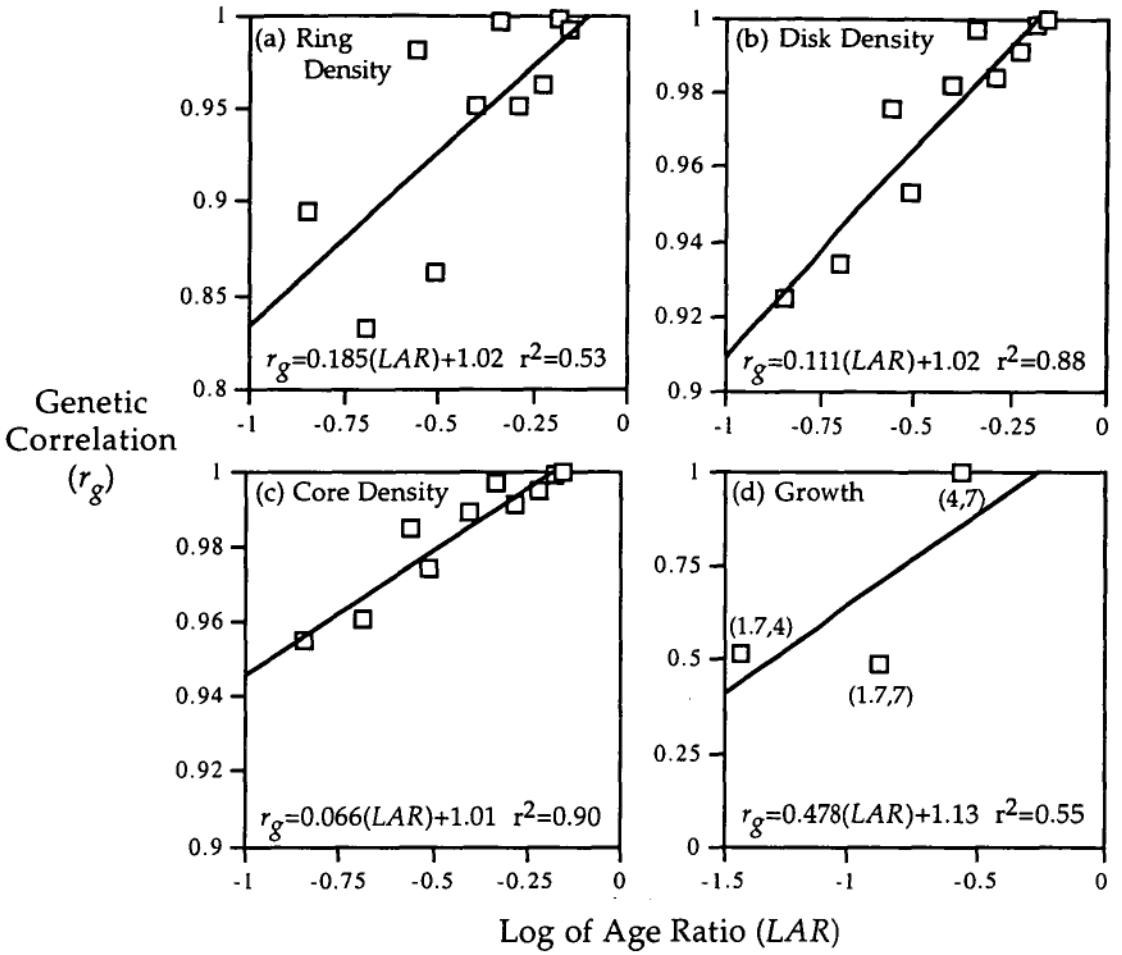

Figure 7.4: Relationship between age-age genetic correlation (r_g) and the natural log of the age ratio (*LAR*) for density and growth traits. Data-point labels in (d) refer to (*early-age, later-age*) - see text.

The age-age correlations for the aggregated density traits, disk density and core density, were clearly well described by Lambeth's (1980) relationship with *LAR* (r^2 0.88 and 0.90 respectively - Figure 7.4). Whilst the observed age-age correlations for individual ring density were not well described by the *LAR* relationship (r^2 0.53) the trend that correlation declines as the age difference increases was still apparent.

The *LAR* coefficients for the density traits were relatively low ranging from 0.066 (cores) to 0.185 (rings) suggesting that very early selection for density may be possible - a low coefficient means correlation declines little with increasing age difference.

The three age-age correlations for growth were not well described by the *LAR* relationship (r^2 0.55). Further, the coefficient of *LAR* for growth was a high 0.478 when previous reported *LAR* coefficients for growth, albeit in conifers, range from 0.177 to 0.345. Two of the three age-age correlations for growth relate to an early age of 1.7 years (20 months), and these two points provided considerable leverage in defining the high *LAR* coefficient (Figure 7.4d). Lambeth (1980) observed that correlations between height measured at one year and later-age growth did not fit the *LAR* relationship observed for later-age correlations. Working with temperate plantation eucalypts both Borralho *et al.* (1992a) and Griffin and Cotterill (1988) concluded height at one year to be an unreliable indicator of subsequent growth performance. It is possible that height at 1.7 years (20 months) is similarly unsuitable for prediction of later-age growth in *E. nitens*. Thus the presented *LAR* relationship for growth (Figure 7.4d) must be considered with caution until further work clarifies the relationship.

Finally, selection of sampled families on the basis of growth rate would have resulted in reduced additive variance for growth in the selected population, with the magnitude of the reduction defined by the accuracy of selection (heritability). The variance of traits showing correlation with growth would have also been reduced in the selected population, with the magnitude of reduction defined by the degree of correlation between growth and the correlated traits (Villanueva and Kennedy 1990). It is probable that the observed relationships between growth and density traits are lower than would have been observed had all families been sampled. However, as more than 50% of families were sampled, the effect on results presented here is assumed to be small, and influence on conclusions probably negligible.

7.4 CONCLUSION

Age-age correlations for density were consistantly high and declined with age difference. Whilst the densities of earlywood and latewood were found to be very strongly related to whole-ring density, they showed lower heritability than whole-ring density. Thus early selection for density using whole-ring density in *Eucalyptus nitens* may be possible.

Age-age correlations for growth were less conclusive and more work is required to clarify the observed trends.

Density appears to be weakly and negatively related to growth in *Eucalyptus nitens* at age seven years.

7.5 ACKNOWLEDGMENTS

The Australian Paper Plantations Pty. Ltd. trial from which the genetic material was sourced (section 7.2.1) was designed and established by Phil Whiteman of Australian Paper Plantations. The early growth measurements, height at 20 months and *dbh* at 4 years, were undertaken by Australian Paper Plantations under the direction of Phil Whiteman and were generously provided for use in this analysis.

The SilviScan analysis system (section 7.2.1) was designed and built by Dr Robert Evans of the Cooperative Research Centre for Hardwood Fibre and Paper Science, and operated by Trish Brennan and Sharee Stringer in the analysis wood samples reported here.

Chapter 8:

Use of Near Infrared Reflectance Analysis in determining genetic parameters for pulp yield in *Eucalyptus nitens*

8.1 INTRODUCTION

Kraft pulp yield is the oven-dry mass of pulp produced from the kraft pulping process per oven-dry mass of wood consumed by the process. Kraft pulping removes the bulk of lignin and extractives, and some hemicellulose, leaving a pulp consisting mainly of cellulose (approximately 70%) and hemicellulose (25%) with some residual lignin (5%) (Smook 1992). Pulp yield is generally measured at a given residual lignin content.

Whilst pulp yield has been shown to have a close relationship with wood chemical characteristics such as cellulose content (Wallis *et al.* 1995), it is also influenced by characteristics of the pulping process: improving the uniformity of chip size or changing the residual lignin content change observed pulp yield (e.g. Crane *et al.* 1987).

Pulp yield has long been considered an important trait with perceived influence on the profitability of kraft pulp enterprises (Dean 1995, Fonseca *et al.* 1995), although it is of lesser importance for breeding than either growth rate or basic density (Chapter 3). If, however, pulp yield is to be considered in breeding programs, the ability to early select requires knowledge of changes in heritability with age and correlations between observations across ages.

The greatest obstacle in breeding to improve pulp yield, however, is that pulp yield can currently only be assessed by actually pulping samples of wood in mini-scale laboratory digesters at a cost of around AUS$500 per

sample (Phil Whiteman[1] *pers. comm.*). Thus, assessment of pulp yield in breeding programs is severely limited by cost, and often assessments are made only at a family level rather than at an individual-tree level. This has limited the study of genetic parameters for pulp yield.

Recently, near infrared reflectance (NIR) analysis has been shown to have application in the indirect assessment of wood-traits of commercial importance to chemical pulping such as pulp yield (Schimleck *et al.* 1996, Michell 1995, Woitkovich *et al.* 1994, Wright *et al.* 1990), and regions of the NIR spectrum have been demonstrated to be heritable (Chapter 6).

This chapter will examine the application of NIR analysis in the prediction of genetic parameters for pulp yield at an individual-tree level. Pulp yield predictions based upon NIR analysis will be made for the inner-most and outer-most growth rings of 588 seven-year-old *Eucalyptus nitens* trees from 50 open-pollinated families in order to determine the genetic relationship between pulp yield of wood laid down at different ages. A routine pulp yield evaluation undertaken by Australian Paper Plantations Pty. Ltd. will be used to calibrate the model for predicting pulp yield from NIR.

8.2 METHODS

8.2.1 Genetic material

Five hundred and eighty-eight seven-year-old *E. nitens* trees were sampled from a progeny trial established by Australian Paper Plantations Pty. Ltd.[2] on two contrasting sites (Table 8.1) in eastern Victoria, Australia. Both trial sites were established as 40 randomised complete blocks, trialing 94 open-pollinated families, giving a total of 40 trees per family per site. Of the 94 trial families, only the 50 families showing the greatest growth were sampled. Six trees per family per site were sampled,

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[1]Phil Whiteman, Technical Manager, Australian Paper Plantations Pty. Ltd., Morwell, Australia

[2]A member of the Amcor group

primarily from six blocks on each site, a total of 588 trees (accounting for missing trees).

Table 8.1: Description of trial sites, site preparation, fertiliser treatment at establishment (after Bennett *et al.* 1989) and site mean *DBH* and density (Chapter 7).

	Site 1	Site 2
Soil	gradational clay-loam	duplex: sandy loam over clay
Latitude (°S)	38	38
Longitude (°E)	146	147
Altitude (m a.s.l.)	200	80
Rainfall (mm yr^{-1})	1006	728
Previous landuse	Radiata pine plantation	agricultural pasture
Site preparation	winged rip, disc plough	ridge plough
Fertiliser at planting (kg ha^{-1})	N 4.2, P 0.9, K 0.9	N 4.2, P 50.9, K 50.9
Mean *DBH* @ 7 years (cm)	16.9	16.3
Mean density @ 7 years (t m^{-3})	0.471	0.541

8.2.2 Family pulp yield evaluation

Four half-stem samples were taken from each tree, each 40 cm long: the first immediately above the ground; the second immediately below merchantable height (5 cm diameter under bark); and the remaining two evenly spaced between the upper- and lower-most samples. The half-stem samples alternated from one side of the tree (as felled) to the other up the stem. All samples were aggregated by family and site (forming a total of 100 aggregate samples - 50 families by two sites) and chipped for analysis of family pulp yield. Family pulp yield (*FAMPY*) was determined using kraft mini-pulping techniques by Amcor Research and Technology (Melbourne, Australia) as part of Australian Paper Plantation's ongoing tree improvement program. Sub-samples from each family/site sample were provided along with *FAMPY* results (provided in confidence) for use in the development of a NIR analysis system of pulp yield evaluation being undertaken within the Cooperative Research Centre for Hardwood Fibre and Paper Science, Melbourne,

Australia (Michell 1995, Michell and Schimleck 1996, Schimleck *et al.* 1996, Schimleck *et al.* 1997).

8.2.3 Sampling for individual-tree NIR

Samples for individual-tree NIR analysis where collected as disks taken from 15% of total tree height (approximately 2.5 metres) and stored at -18°C until sample preparation for NIR analysis.

Cores, approximately 10 mm wide by 10 mm high, were cut from the frozen disks using a band-saw. The inner-most and outer-most growth-rings were cut from the cores using a wood chisel. Ring samples from opposite ends of the core were combined. The inner-most growth ring, defined as Ring 3, represents wood deposited when the trees were 3 years old. The outer-most growth ring, defined as Ring 7, represents wood deposited in the last growing season prior to sampling. Samples were allowed to dry slowly in air before being reduced to meal by milling in a Wiley Mill No. 4 according to AS1301 002s-91 (Anon. 1995). The woodmeal was mixed and two (replicate) 1.5 g samples were taken for NIR analysis (making a total of 2352 samples: 588 trees by two sampled growth rings by two replicate samples per ring).

8.2.4 NIR analysis

The NIR spectra were measured as diffuse reflection from the woodmeal samples contained in micro-sample cups in a spinning holder using a NIRSystems Inc. Model 5000 scanning spectrophotometer with a ceramic standard as reference. Reflectance was measured at 2 nm intervals over the range 1100 - 2500 nm and a total of 50 scans were accumulated for each sample and the scans averaged by the Model 5000 software to produce one reflectance spectrum per sample (i.e. a total of 2352 spectra: two replicate spectra per ring, by two rings per tree, by 588 trees). The spectra were converted to the second derivative mode using the instrument's software with a segment of 10 nm and a gap of 20 nm. The second derivative mode was used to minimise the effects on the reflectance spectrum of differences in particle size and to give improved band resolution (Barton 1989).

8.2.5 NIR analysis calibration model

The NIRSystems Inc. Model 5000 has a facility for construction of a calibration model between the observed NIR spectra and the trait of interest. Figure 8.1 depicts the construction and use of the NIR calibration model. Each family/site aggregate sample was ground to woodmeal and the NIR spectra collected. The laboratory measured kraft pulp yield value for the sample (*FAMPY*, provided by Australian Paper Plantations) was entered into the Model 5000 and the instrument constructed a relationship between the 700-band NIR spectra and pulp yield, using principal component analysis techniques (Schimleck *et al.* 1996). The calibration model was used by the Model 5000 to provide pulp yield estimates from the observed NIR spectra for the individual-tree inner- and outer-most growth rings.

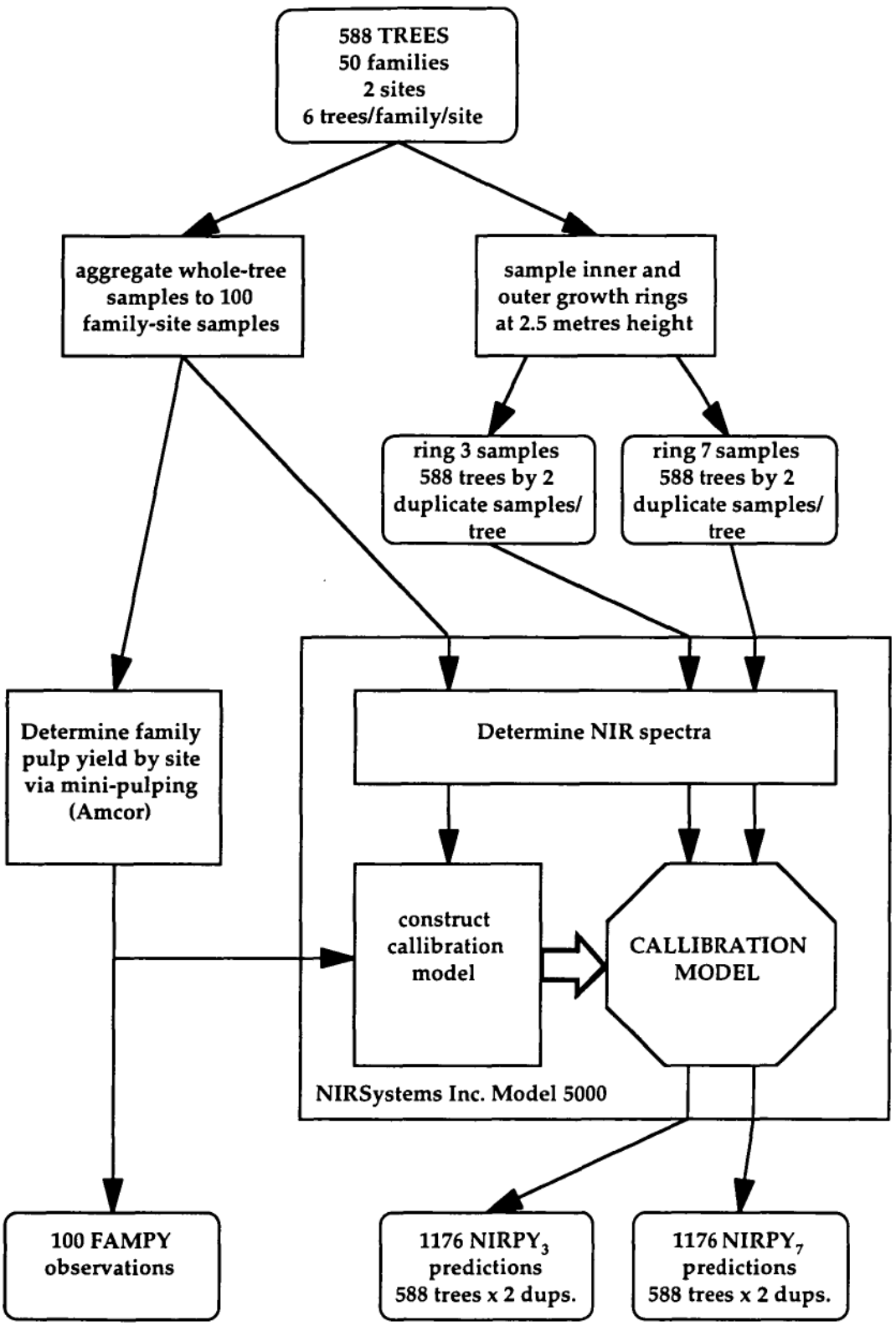

Figure 8.1: Use of the NIRSystems Inc. Model 5000 in the construction and application of a calibration model relating NIR spectra and pulp yield.

8.2.6 Statistical analysis

Variance components for NIR predicted pulp yield (*NIRPY*) were estimated using the model, in matrix notation (after Henderson 1984):

[8.1] $$\mathbf{y} = \mathbf{Xb} + \mathbf{Z_1a} + \mathbf{Z_1t} + \mathbf{Z_2i} + \mathbf{e}$$

where **y** is a vector of observations (*NIRPY*, for both inner and outer rings), **b** is a vector of fixed effects (site, replicates within site and seed collection area), **a** is a vector of additive effects of individual trees (random effects), **t** is a vector of permanent environmental (between tree) effects (random effects), **i** is a vector of family-by-site interaction effects (random effects), **e** is the vector of residuals (within tree effects) and **X**, $\mathbf{Z_1}$ and $\mathbf{Z_2}$ are incidence matrices relating observations to the effects in the model. Variances, covariances, and standard errors were estimated using REML VCE software using a quasi-Newton algorithm (Groeneveld 1995).

Heritability (h^2) was calculated after:

[8.2] $$h^2 = \frac{\sigma_a^2}{\left(\sigma_a^2 + \sigma_t^2 + \sigma_i^2\right)}$$

where σ^2_a is the additive variance; σ^2_t is the variance of the permanent environmental (between tree) effect; and σ^2_i is the variance of family-by-site interaction. Whilst the trial families were analysed as open-pollinated families, inbreeding was assumed and a coefficient of relationship of 0.4 rather than 0.25 was used (after Volker *et al.* 1990).

Genetic correlation (r_g) was calculated after:

[8.3] $$r_g = \frac{\mathrm{cov}_{3,7}}{\sqrt{\sigma^2_{a_3}\sigma^2_{a_7}}}$$

where $\mathrm{cov}_{3,7}$ is the additive covariance between *NIRPY3* and *NIRPY7*; σ^2_{a3} and σ^2_{a7} are the additive variances of *NIRPY3* and *NIRPY7* respectively.

Repeatability (ρ) was calculated after:

[8.4] $$\rho = \frac{\left(\sigma_a^2 + \sigma_t^2 + \sigma_i^2\right)}{\left(\sigma_a^2 + \sigma_t^2 + \sigma_i^2 + \sigma_e^2\right)}$$

where σ^2_e is the between-sample variance (i.e. the variation between the two replicate observations).

The level of family by site interaction (*GxE*) is defined here as ratio of the variance of family-by-site interaction (σ^2_i) and the total variance between trees:

[8.5] $$GxE = \frac{\sigma_i^2}{\left(\sigma_a^2 + \sigma_t^2 + \sigma_i^2\right)}$$

8.2.7 NIR pulp yield versus laboratory pulp yield

For comparison with "true" family mean pulp yield determined using kraft mini-pulping (*FAMPY*) the Ring 3 and Ring 7 NIR predictions (*NIRPY3* and *NIRPY7* respectively) were aggregated to family *NIRPY* values after:

[8.6] $$FAMNIRPY_{fs} = \frac{\sum_{t=1}^{6}\left(\frac{2NIRPY7_{tfs} + NIRPY3_{tfs}}{3}\right)}{\sum_{t=1}^{6} VOL_{tfs}}$$

where $FAMNIRPY_{fs}$ is the NIR predicted family mean pulp yield of the f^{th} family on the s^{th} site; and VOL_{tfs} represents the volume of the t^{th} tree within the f^{th} family on the s^{th} site.

8.3 RESULTS

8.3.1 Observed pulp yield

Pulp yield was consistently higher on Site 1 than Site 2 (Table 8.2). *NIRPY* was consistently higher in the outer-ring (Ring 7) than the inner-ring (Ring 3).

Table 8.2: Mean and range of observed pulp yield by site.

Pulp yield	Site	mean	range
FAMPY	Site 1	52.1%	50.3 - 54.0%
	Site 2	49.7%	46.8 - 51.7%
$NIRPY_3$	Site 1	47.0%	44.0 - 51.7%
	Site 2	46.0%	41.5 - 53.1%
$NIRPY_7$	Site 1	56.2%	46.4 - 61.7%
	Site 2	54.2%	48.0 - 58.9%

8.3.2 Genetic parameters

Individual heritabilities of *NIRPY* were low in both growth rings examined (Table 8.3). Repeatability of prediction was, however, extremely high. Genotype-by-environment interaction was very low.

Table 8.3: Individual heritability (h^2) and standard errors (in parenthesis), repeatability (ρ), and the proportion of total variation explained by genotype-by-environment interaction (*GxE*).

pulp yield	h^2	ρ	GxE
NIRPY3	0.21 (0.06)	0.98	0%
NIRPY7	0.13 (0.06)	0.88	4%

NIRPY3 and *NIRPY7* showed a strong genetic relationship (rg = 0.72, *S.E.* 0.22).

8.3.3 Laboratory pulp yield across sites

There was only moderate agreement (r = 0.56), albeit significant, between the family mean pulp yield across the two sampled sites (Figure 8.2).

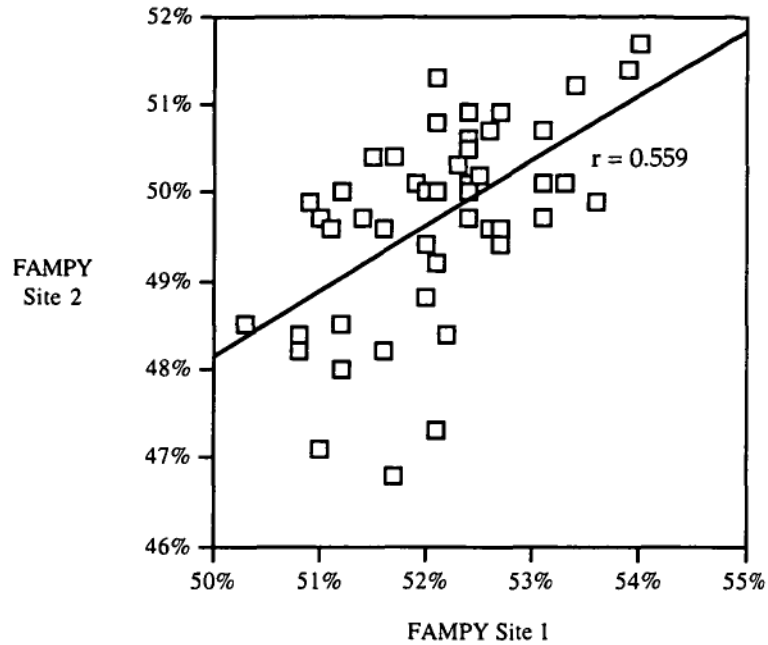

Figure 8.2: Family mean pulp yield (*FAMPY*) across the two sampled sites - each point represents one family.

8.3.4 NIR pulp yield versus laboratory pulp yield

The relationship between the pulp yield estimates after kraft mini-pulping (*FAMPY*) and the family estimates derived from aggregated *NIRPY* predictions (*FAMNIRPY*) was weak (Figure 8.3).

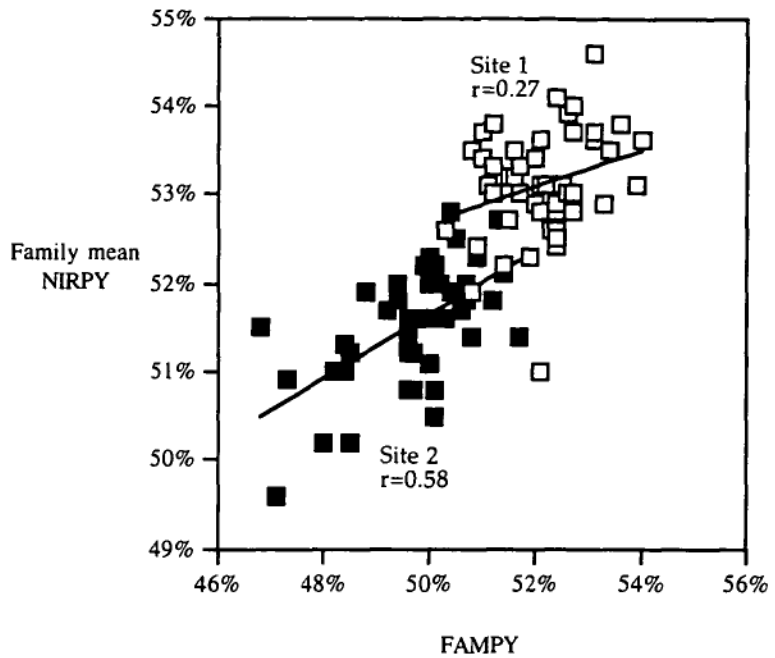

Figure 8.3: The relationship between pulp yield predicted via NIR analysis (*FAMNIRPY*) and family pulp yield as measured from whole-tree samples (*FAMPY*), by site (*r* is the correlation coefficient).

8.4 DISCUSSION

The more fertile Site 1 showed a higher pulp yield than Site 2 (Table 8.2) which compares with a previously reported higher growth rate (although the difference was small), and lower density (Table 8.1).

The observed heritabilities of *NIRPY3* and *NIRPY7* were low (0.21 and 0.13 respectively) but not unreasonable in comparison with previously reported heritabilities in eucalypts: 0.19 (*E. globulus*, Borralho *et al.* 1993), 0.24 (*E. grandis*, Clark 1990), 0.3 (*E. obliqua*, Matheson *et al.* 1986), and 0.34 (*E. globulus*, Dean *et al.* 1990) - note that these values have been adjusted for a coefficient of relationship of 0.4 after Volker *et al.* (1990).

The genetic relationship between the predicted pulp yields of the inner and outer annual rings (*NIRPY3* and *NIRPY7* respectively) was a high 0.72, suggesting early selection for pulp yield may be possible.

The repeatability of the pulp yield predictions was very high (0.88 and 0.98 - Table 8.2) suggesting the NIR analysis system to be a precise tool (repeated predictions are in agreement), however the accuracy of the pulp yield predictions (*NIRPY*) is much less certain.

Firstly, whilst the pulp yield values predicted using NIR analysis showed minimal genotype by environment interaction (Table 8.2), there was only a poor relationship between the more accurate family pulp yield values (*FAMPY*) across the two sites (Figure 8.2). This raises a question as to the accuracy of the laboratory pulp yield values upon which calibration was based.

The relationship between measured and predicted pulp yields (*FAMPY* and *NIRPY* respectively) was low (Figure 8.3) although both traits are estimates and hence have associated sampling and experimental error. The *FAMPY* values were derived from large samples from various places within each standing tree, whereas the *NIRPY* predictions were made from very small samples taken at approximately 2.5 metres from the ground. The poor agreement may reflect substantial differences in within-tree variation and large sampling errors associated with using cores to predict whole-tree pulp yield.

The calibration model, which is based upon samples collected over the length of the tree stem and over six trees, is also of concern. The calibration samples encompass the total pulp yield variation both within a tree and between trees within a family - both of which may be considerable. The small core samples from which pulp yield was predicted, on the other hand, contain only the variation encompassed in a single growth ring, being mainly the differences between the pulp yield of earlywood and latewood. Thus the calibration model is based upon samples with high within-sample variation and low between-sample variation, but it is being used to make predictions from samples with (conversely) low within-sample variation and high between-sample variation. The range of pulp yields in the calibration set was 47% to 54% (Table 8.1) whilst the predictions ranged from 42% to 62%! The considerable differences between the samples used for the calibration model and the prediction samples is highlighted when the levels of the principal components of the samples are compared (see Schimleck *et al.* 1996). Figure 8.4 presents the "scores" in the first and second principal components for 50 calibration samples, 50 Ring 3 samples and 50 Ring 7

samples (due to limitations of the NIRSystems Inc. Model 5000 only 50 samples in each group could be represented). It is apparent that many of the Ring 3 and the Ring 7 samples fall outside the reliable prediction space of the model.

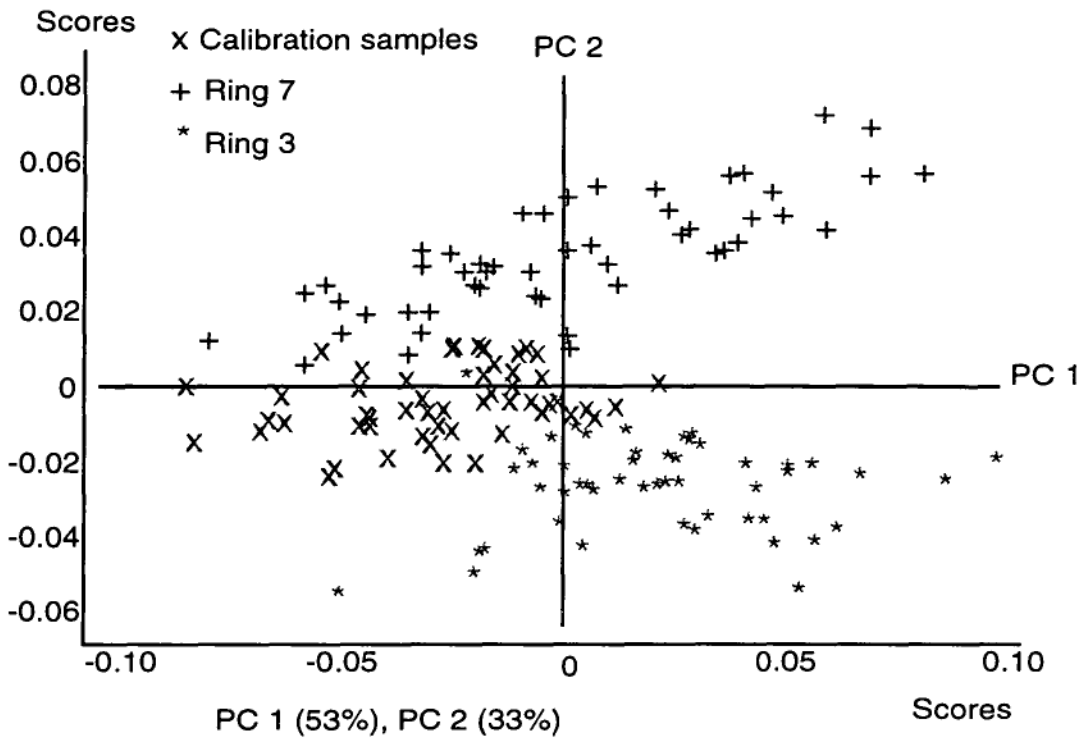

Figure 8.4: Two-dimensional principal components' scores plot for a selection of 150 *E. nitens* samples used in this study. Figure courtesy of Schimleck (1996).

It must be concluded that the calibration model used in this study was not suitable for determining pulp yield of small samples taken from a single location in the stem of a tree. To rectify this deficiency, a better model is required and a new project to develop this model is currently underway. In short, the project involves collecting short stem sections from other trees in the same trial, manually chipping the outer-most and inner-most rings, and using a micro-pulping system currently under development within the Cooperative Research Centre for Hardwood Fibre and Paper Science to provide a more suitable set of calibration samples. To date all samples have been collected and processed using the NIR analysis system, but variable results from the micro-pulping have delayed further progress.

It must be noted, however, that the application of NIR analysis in the prediction of pulp yield and other wood traits of commercial importance is currently under development. Whilst the calibration model used in this study may have been less than ideal for the prediction of pulp yield from very small samples, NIR analysis has shown promise in the indirect evaluation of wood chemical traits (Schimleck *et al.* 1997).

8.5 CONCLUSIONS

Whilst this study indicated a strong genetic relationship (r_g = 0.7) between the pulp yield of wood deposited in the third and in the seventh years of a tree's growth, other aspects of this study leave this result in question. The heritability of predicted pulp yield is lower than expected, and there is little agreement between the pulp yields predicted via NIR analysis and laboratory kraft pulp yields determined for family aggregated samples sourced from the same trees.

Whilst the NIR analysis system of prediction appeared to be very precise, showing considerable agreement between repeated measurements, further work should be undertaken to produce a more appropriate calibration model upon which predictions can be based.

8.6 ACKNOWLEDGMENTS

Laurie Schimleck of the Cooperative Research Centre for Hardwood Fibre and Paper Science performed the NIR analysis (sections 8.2.4 and 8.2.5), using techniques he developed whilst working towards his Ph.D. (Schimleck 1996). The work reported in this chapter was thus reported as a chapter of Laurie Schimleck's Ph.D. dissertation, however Laurie documented the results from the perspective of the application of the NIR analysis systems rather than the determination of genetic parameters reported here.

Dr. Alan Farrington of Amcor Research and Technology performed the assessment of the family pulp yield (section 8.2.2).

Chapter 9:

Early selection for kraft pulp in plantation eucalypts

This chapter is currently under internal review by CSIRO Forest and Forest Products review prior to submission to *New Forests*:

Greaves, B.L., Borralho, N.M.G. and Raymond, C.A. (in review) Early selection for kraft pulp in plantation eucalypts. *New Forests*

9.1 INTRODUCTION

Expected gain due to early selection can be determined using quantitative genetics theory if the heritability at selection age, the age-age genetic correlations between selection age and rotation age, and the economic weights of each trait at rotation age are known.

Chapter 3 derived a breeding objective for temperate plantation eucalypts grown for kraft pulp, defining basic density and growth rate as the traits of maximum importance to breeding towards reducing the cost of kraft pulp production, and presenting economic weights for these traits.

Chapter 7 presented heritabilities and age-age correlations for density in *Eucalyptus nitens* demonstrating a strong relationship between age-age genetic correlation and the natural log of the ratio of ages (*LAR*, after Lambeth 1980).

Heritabilities and age-age correlations for growth in eucalypts have been reported for *E. grandis* (Van Wyk 1990), *E. globulus* (Borralho *et al.* 1992b) and *E. nitens* (Chapter 7). Lambeth (1980) found that age-age correlations for growth showed a strong linear relationship with *LAR* and that the relationship was robust across conifer species and growing environments examined.

Traditionally, optimum *biological* selection age has been defined as the selection age when average annual gain towards the breeding objective is maximum (Kang 1985). The optimum *biological* selection age, however, does not take account of the time value of returns from genetic improvement. For example, a gain of $20 (per tonne of pulp produced) resulting from a six year breeding cycle would have the same *biological* value as a $40 gain from a 12 year breeding cycle. Alternatively, the optimum *economic* selection age has been defined as the selection age when the total discounted value, or present value, of all future returns is maximum (e.g. McKeand 1988).

This paper will draw on published and previously derived genetic parameters for density and growth for plantation eucalypts to determine the optimum *biological* and *economic* ages for early selection towards the breeding objective of minimising the total production cost of unbleached eucalypt kraft pulp (Chapter 3).

9.2 METHODS

9.2.1 Breeding objective traits

The traits in the breeding objective which are to be improved are density and standing volume at rotation age (15 years) (after Chapter 3). Assumed genetic parameters and economic weights for these traits are presented in Table 9.1.

Table 9.1: Assumed additive standard deviations (σ_a) and economic weights for the traits in the breeding objective (after Chapter 3). The economic weights presented here represent the saving in total pulp cost at the end of the rotation.

Objective trait	unit	σ_a	economic weight ($ per unit increase at rotation end)
density	$t\ m^{-3}$	0.022	726
standing volume	$m^3\ ha^{-1}$	38	0.559

9.2.2 Trends in heritability and age-age correlations

The age trend in heritability (h^2) for density assessed via extraction of cores[1] (after parameters presented in Chapter 7) was modelled as:

$$[9.1] \quad h^2 = 0.235 \log_e(age) + 0.065$$

where *age* is the selection age in years. The relationship closely described the heritabilities reported in Chapter 7 (r^2=0.97).

The trend age-age genetic correlation (r_g) for density (after Chapter 7) was:

$$[9.2] \quad r_g = 0.066(LAR) + 1.01$$

where (after Lambeth 1980):

$$[9.3] \quad LAR = \log_e\left(\frac{\text{early age}}{\text{later age}}\right)$$

Of the reported heritabilities and age-age correlations for growth in eucalypts (Van Wyk 1990, Borralho *et al.* 1992b, Chapter 7), the parameters reported by Van Wyk were chosen to represent eucalypts in general. Firstly, the genetic parameters predicted from Van Wyk's data fall within the 95% confidence limits of the relationships fitted for the other reported data, and secondly, the relationships developed from Van Wyk's data show the best fit (r^2) of the heritability and age-age correlation relationships for growth in eucalypts.

The trend in heritability of growth with age derived from heritabilities for volume reported by Van Wyk (1990) adjusted to equate to a coefficient of relationship of 0.4 (after Volker *et al.* 1990), was:

$$[9.4] \quad h^2 = 0.129 \log_e(age) + 0.051$$

which closely described Van Wyk's reported heritabilities (r^2=1.00).

The trend in age-age correlation with *LAR*, using age-age genetic correlations for growth traits as reported by Van Wyk (1990), was:

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[1] Unless otherwise stated, selection for density is assumed to be undertaken via assessment of extracted cores

[9.5] $r_g = 0.270(LAR) + 1.09$

which closely described Van Wyk's reported correlations (r^2=0.94).

The genetic correlation between density and volume at rotation age is assumed to be -0.2 and the phenotypic correlation between density and growth at selection age is assumed to be zero (after Chapter 7). The genetic correlation between density at selection age and volume at rotation age ($r_{DENS(s).VOL(r)}$) was approximated by:

[9.6] $r_{DENS(s).VOL(r)} = r_{DENS(s).DENS(r)} \times r_{DENS(r).VOL(r)}$

where ($r_{DENS(s).DENS(r)}$) is age-age genetic correlation for density and ($r_{DENS(r).VOL(r)}$) is the genetic correlation between density and volume at rotation age. Similarly, the genetic correlation between volume at selection age and density at rotation age ($r_{VOL(s).DENS(r)}$) was approximated by:

[9.7] $r_{VOL(s).DENS(r)} = r_{VOL(s).VOL(r)} \times r_{DENS(r).VOL(r)}$

9.2.3 Expected gain due to selection

Gain towards a multi-trait objective due to multi-trait selection was predicted as, in matrix notation (White and Hodge 1989):

[9.8] $G = i.\left(\mathbf{w'A'.V^{-1}.A.w}\right)^{0.5}$

where G is the gain in the objective trait; i is the selection intensity (2.665 for an assumed selection pressure of 1%); $\mathbf{w}$ is a vector of economic weights for the objective traits; $\mathbf{A}$ is the additive covariance between the selection traits and the objective traits; and $\mathbf{V}$ is the phenotypic (co)variance between the selection traits.

The *propagation delay*, given as the time needed for improved genetic material to be deployed for subsequent generation trials or into operational plantations, was assumed to be four years (Peter Gore[2] pers. com.).

[2]Peter Gore, Eucalypt Program Manager, Southern Tree Breeding Association, Australia

Optimum *biological* age of selection is the selection age when the average annual gain is at a maximum (Kang 1985). Average annual gain was calculated after (e.g. Borralho *et al.* 1992b, Matheson *et al.* 1994):

$$[9.9] \quad G_{yr} = \frac{G}{\left(t_s + t_p\right)}$$

where G_{yr} is the average gain towards the breeding objective per year; t_s is the age of selection; and t_p is the propagation delay.

Optimum *economic* age of selection is the selection age when the present value of all future gains is at a maximum. The present value of all future gains (PV_G) was calculated after (Appendix 9.1):

$$[9.10] \quad PV_G = \sum_{b=1}^{\infty} \sum_{n=1}^{t} \frac{b.G}{\left[1+d\right]^{(t.b+r+n-1)}}$$

where b represents the breeding cycle number (1 to ∞); t is the breeding cycle length; n represents the deployment year within the breeding cycle (1 to t); G is the incremental gain per breeding cycle (after Eqn. 9.8); r is the rotation length; and d is the discount rate.

The discount rate (d, Eqn. 9.10) was assumed to be 5% (after Chapter 3), however the sensitivity of optimum economic selection age to discount rate was examined.

9.3 RESULTS AND DISCUSSION

Figure 9.1 depicts the expected annual gain towards the objective versus selection age for (i) combined selection for density and growth; (ii) single-trait selection for density; and (iii) single-trait selection for growth.

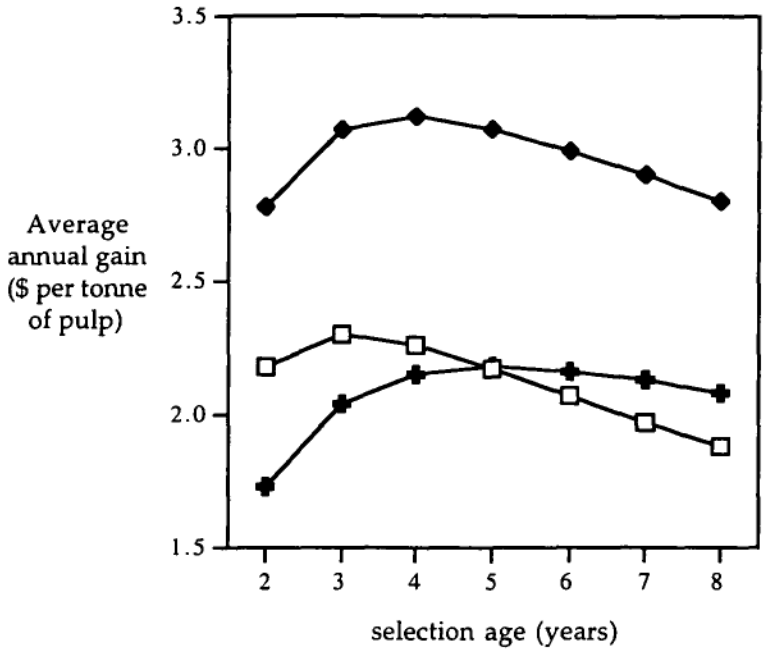

Figure 9.1: Average annual gain (savings in total pulp cost) versus selection age, for: combined selection on density and growth (◆); single-trait selection for density (□); and single-trait selection for growth (✚). Density is assumed to be assessed via increment cores.

The optimum *biological* selection age for density was three years, whilst the optimum *biological* selection age for growth was five years (Figure 9.1). The optimum *biological* age for dual-trait selection to maximise the average annual reduction in total pulp cost was four years.

Borralho *et al.* (1992b) reported four years to be the optimum age for early selection for growth in temperate eucalypts for rotation lengths of 8 to 18 years but cautioned that optimum time of early selection is probably related to tree size rather than tree age *per se*. Cotterill and Dean (1988) similarly concluded absolute size to be more important than age in determining early selection age in radiata pine. Reported optimum selection ages vary with species and expected rotation length, from four years (McKeand 1988: Loblolly pine, 25 year rotation) to 12 years (Gonzalez and Richards 1988: Douglas fir, 50 year rotation).

Figure 9.2 depicts the present value of all future gains towards the objective versus selection age for (i) combined selection for density and growth; (ii) single-trait selection for density; and (iii) single-trait selection for growth.

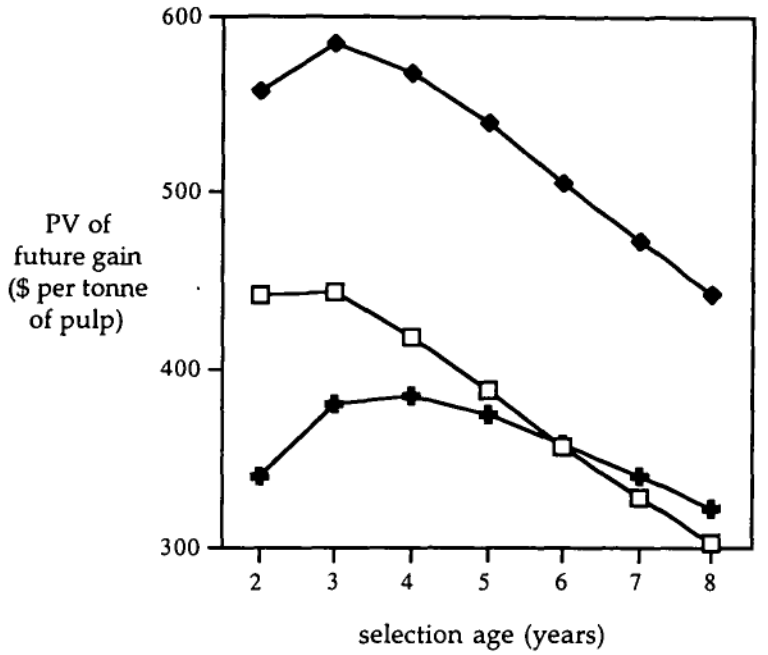

Figure 9.2: Present value of all future gains (after Eqn. 9.10, assuming a discount rate of 5%) versus selection age, for: combined selection on density and growth (◆); single-trait selection for density (□); and single-trait selection for growth (✚).

The optimum *economic* selection age for density was three years, whilst the optimum *economic* selection age for growth was four years (Figure 9.2). The optimum *economic* age for dual-trait selection to maximise the present value of all future gains was three years.

Whilst a discount rate of 5% has been used in the present value analysis (after Chapter 3), published discussion regarding the choice of discount rate has been considerable (see Price 1973 and Klemperer *et al.* 1994). Reducing the discount rate from 5% to 1% increased the *economic* selection age from three to four years. Discount rates as high as 10%, whilst distorting the response of gain to selection age, did not reduce the optimum *economic* selection age from three years. McKeand (1988) similarly concluded discount rates from 2% to 10%, whilst impacting upon expected gains, did not alter optimum *economic* selection age.

Optimum *biological* and *economic* selection ages are also dependent upon the assumed trends in age-age correlations of the selection traits. Whilst the *LAR* coefficient for growth used in this study was 0.246 (Eqn. 9.5), reported coefficients vary from 0.177 (Riemenschneider 1988 - *Pinus banksiana*) to 0.478

(Chapter 7 - *E. nitens*). Similarly, the coefficient of *LAR* for density used in this study was 0.066 (Eqn. 9.2), yet the coefficient to be dependent upon the method of density assessment and might be as high as 0.185 (Chapter 7). Table 9.2 presents the optimum *biological* and *economic* selection ages determined over the range of reported *LAR* coefficients.

Table 9.2: Optimum *biological* and *economic* selection age for combined selection for density and growth in relation to changes in *LAR* coefficients (Eqn.s 9.2 and 9.5). Numbers in *italics* represent assumed values.

Optimum selection age	Coefficient of *LAR* for growth	Coefficient of *LAR* for density	
		0.066	0.185[3]
Optimum *biological*	0.177[1]	4	4
selection age	*0.246*	4	5
	0.478[2]	5	7
Optimum *economic*	0.177[1]	3	3
selection age	*0.246*	3	3
	0.478[2]	3	4

[1] Riemenschneider (1988) - *Pinus banksiana*
[2] Chapter 7 - *E. nitens*
[3] Chapter 7 - *E. nitens*, coefficient for selection via Pilodyn

It was apparent (Table 9.2) that optimum *economic* selection age for combined trait selection for density and growth was very robust to changes in the assumed age-age correlation trends for both traits. *Biological* selection age was somewhat more dependent upon assumptions made but even considerable change in the coefficient of *LAR* for either trait shifted the optimum age by only one year (Table 9.2).

It must be noted that the optimum *economic* ages as presented (Figure 9.2) do not take account of future costs. The costs per breeding cycle are relatively fixed and earlier selection ages will result in more breeding cycles and thus higher future costs. The present value (assuming a discount rate of 5%) of all future trial and assessment costs in a typical breeding program vary from approximately $440,000 for a selection age of two years to $180,000 for a selection age of eight years. Whilst the difference between these costs is considerable, the present value of all future savings in total pulp cost, assuming a modest annual pulp production of 100,000 tonnes, are in the

order of $50M, and thus inclusion of trial and deployment costs does not alter optimum economic selection age.

Further, the determination of both the biological and economic optimum ages of selection implicitly assume that both gain per generation and rotation length will remain constant with subsequent breeding cycles. In reality, both may change with continued breeding effort (Kang 1985), although Johansson and Löfgren (1985) found otherwise. These simplifications seem appropriate for the determination of optimum selection age in the absence of greater knowledge, given the robustness of the results even to major changes in assumed parameters.

Finally, there are other practical considerations when deciding on an early selection age. Firstly, it must be possible to induce flowering once selections are made, although the use of paclobutrasol appears to have resolved this problem with eucalypts (Reid *et al.* 1995). Secondly, early density assessment via extraction of cores may be difficult in small trees.

9.4 CONCLUSION

In selection for density and growth towards reducing the cost of producing unbleached kraft pulp in eucalypts, the optimum *biological* selection age (the selection age where average annual gain is maximised) was four years, whilst the optimum *economic* selection age (the selection age where the present value of all future gains is maximised) was three years. These conclusions were robust to changes in assumptions of trends in genetic parameters and interest rates used in analysis.

APPENDIX 9.1

The present value of all future gains is calculated as the total of all discounted future gains. The first savings in total pulp cost due to breeding (G, Eqn. 9.8) will occur at a time equal to the breeding cycle (the selection age plus the propagation delay) plus the rotation length (the time taken to grow the improved trees, assumed to be 15 years). The savings in pulp cost will be constant over subsequent years until a second breeding cycle increases the total gain to $2G$ at a time equal to two breeding cycles plus one rotation length. Thus future gains will increase incrementally with each subsequent breeding cycle (Figure A9.1).

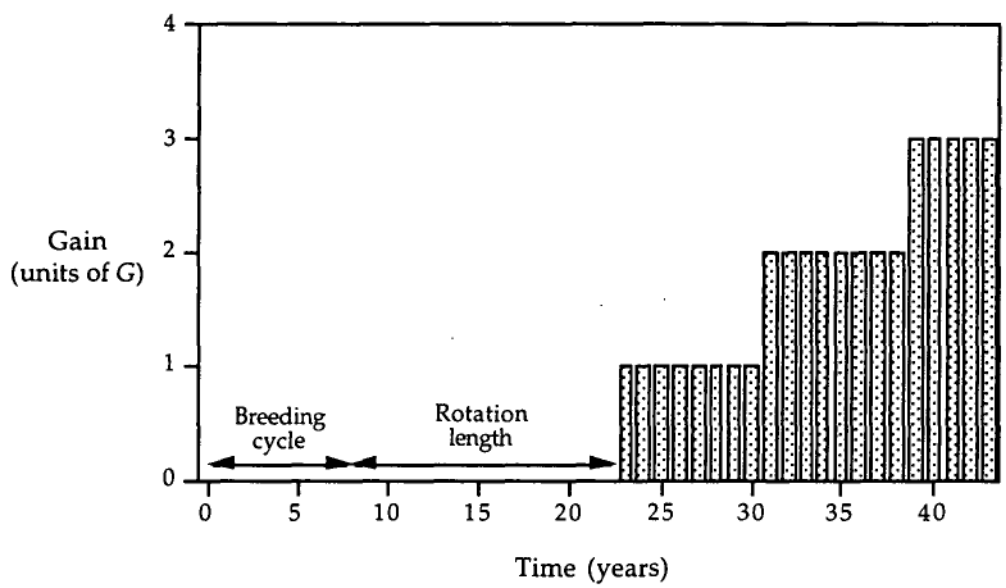

Figure A9.1: Expected gain due to breeding (G, savings in total pulp cost) versus time, assuming an eight year breeding cycle and a fifteen year rotation. The "Breeding Cycle" represents the selection age plus the propagation delay.

The first gain from breeding, G, will occur at a time equal to the breeding cycle length (t) plus the rotation length (r). The PV of the first year of the first gain for discount rate i is thus:

$$PV_G = \frac{G}{(1+d)^{(t+r)}}$$

The PV of all gain from the first breeding cycle (prior to the gain increment due to the second breeding cycle) is thus:

$$PV_G = \sum_{n=1}^{t} \frac{G}{[1+d]^{(t+r+n-1)}}$$

where n represents the deployment year within the breeding cycle (1 to t). After a time equal to two breeding cycles plus one rotation length, gain is incremented to $2G$. Thus the PV of all gain from the second breeding cycle (prior to the gain increment due to the third breeding cycle) is thus:

$$PV_G = \sum_{n=1}^{t} \frac{2G}{[1+d]^{(2t+r+n-1)}}$$

Thus, the present value of all future gains (PV_G) can be determined after:

$$PV_G = \sum_{b=1}^{\infty} \sum_{n=1}^{t} \frac{b.G}{[1+d]^{(t.b+r+n-1)}}$$

where b represents the breeding cycle number (1 to ∞).

Chapter 10:

Discussion

The work presented in this thesis can be divided into three main sections: (i) the development of a breeding objective (Chapters 2, 3 and 4); (ii) methods for assessing traits of importance towards achieving the objective (Chapters 5 and 6); and (iii) early selection towards achieving the objective (Chapters 7, 8 and 9).

10.1 BREEDING OBJECTIVE

Recent work in the area of breeding objectives for eucalypts (Borralho *et al.* 1993) assumed pulping costs ($C_{pulping}$) to be directly and inversely related to the density (*DENS*) and pulp yield (*PY*) of the logs delivered to the mill, i.e.:

$$[10.1] \quad C_{pulping} \propto \frac{1}{DENS.PY}$$

In Chapter 2 the effect on total pulp cost of improving density and pulp yield was investigated in greater detail. The cost of kraft pulping was demonstrated to be related to basic density and pulp yield:

$$[10.2] \quad C_{pulping} \propto \frac{1}{(DENS)^{0.5}(PY)^{0.7}}$$

Thus the advantage due to improving either density or pulp yield would be overestimated if cost was assumed to be directly related to both traits (Eqn. 10.1). The magnitude of the overestimate in savings can be determined assuming:

- an annual pulp production of 500,000 tonnes;
- a base pulping cost of $200 per tonne (Table 2.2);
- an expected gain in density from 0.500 to 0.540 t m^{-3} (Table 4.5); and
- expected gain in pulp yield from 0.500 to 0.509 t t^{-1} (Table 4.5).

The estimated gains are:

- saving in pulp cost (Eqn. 10.1): \$18 per tonne, or \$9M per year; and
- saving in pulp cost (Eqn. 10.2): \$10 per tonne, or \$5M per year.

Thus future annual gain would have been overestimated by \$4M per year by assuming pulping cost to be directly and inversely related to both density and pulp yield (Eqn. 10.1).

A key assumption underlying the use of Equation 10.2 is that all costs in the mill are variable, and that the mill hardware (capital) can be made bigger or smaller to optimally suit the delivered wood, with corresponding change in the capital cost of pulping. This is a valid assumption as breeding decisions made now will not change mill costs until at least 20 years into the future, by which time existing mills may be largely upgraded and more optimally designed to suit the improved genetic material.

In Chapter 3 the derived pulping cost functions (Table 2.1) were incorporated into a total profit function for pulp production. Economic weights, the improvement towards the objective of reducing total pulp cost for a unit change in a trait, were derived (Table 10.1). These economic weights do not, however, reflect the relative importance of each trait to breeding. Firstly, the economic weight for density is \$349 but this represents an increase in density of one t m^{-3} from (say) 0.5 to 1.5 t m^{-3}, whereas the realistic range of density in *E. globulus*, for example, is 0.4 to 0.6 t m^{-3}. Secondly, the degree of exploitable genetic variation and the accuracy of predicting genetic value (the square-root of heritability in the case of phenotypic selection) differ amongst traits. The relative value of a given trait for breeding can be described as the relative improvement towards the objective (G_t) for any given selection intensity applied to that trait (after Eqn. 3.9):

$$[10.3] \quad G_t \propto \frac{\mathbf{a}_{a.t}\mathbf{w}}{\sigma_{p.t}}$$

where: $\mathbf{a}_{a.t}$ is a vector of additive covariances between the selection trait and the other traits in the objective; $\sigma_{p.t}$ is the phenotypic variance of the selection trait; and $\mathbf{w}$ is a vector of economic weights of all traits in the objective.

The relative values to breeding for each trait in the breeding objective are presented in Table 10.1. Table 10.1 also presents the expected annual

savings, for an enterprise producing 500,000 tonnes of pulp annually, due to selecting for each trait individually and for multi-trait selection.

Table 10.1: Economic weights, relative value to breeding (after Eqn. 10.3) and expected gain (annual savings) due to selection (assuming an annual pulp production of 500,000 tonnes), for traits in the breeding objective. Relative value to breeding for the multitrait objectives (*VOL, DENS, PY & FORM* and *VOL & DENS*) were derived empirically (Chapter 3).

trait	economic weight	relative value to breeding	annual savings
VOL	\$0.269 m^{-3} ha^1	3.2	\$22M
DENS	\$349 t^{-1} m^3	3.6	\$24M
PY	\$411 t_p^{-1} t_w	1.9	\$13M
FORM	\$1.15 (score point)$^{-1}$	1	\$7M
VOL, DENS, PY & FORM	-	4.9	\$33M
VOL & DENS	-	4.7	\$31M

Density and volume production were the most important traits to breeding (Table 10.1) - that is, they are the traits which will provide the greatest return for a given breeding effort. Breeding programs for temperate eucalypts for kraft pulp production which primarily aim to improve growth rate (e.g. Cameron *et al.* 1989) or pulp yield (e.g. Dean 1995) would therefore forgo significant savings in future pulp cost (Table 10.1). This clearly demonstrates Amer's (1994) view that in all cases a more accurate definition of the breeding objective represents an opportunity for the forest grower to increase gains from breeding at virtually no extra cost.

Economic weights (Table 10.1) are little more than an interpretation of a production function, and where a production function is complex, its application via economic weights may be considerably more simple than direct substitution of breeding values into the production function. Economic weights are often reported as if they are absolute values (e.g. Dean *et al.* 1990), yet non-linearity of the production function with respect to a trait will result in the real economic weight changing across the exploitable range of that trait. Chapter 4 examined the application, via economic weights, of the production function developed in Chapter 3. Non-linearity and interdependence with respect to the objective traits resulted in gains being

overestimated when selection pressures typical of tree breeding programs were applied - the gain associated with selecting the best 1% of individuals was overestimated by 25%, equivalent to overestimating the annual gain by $8M for a 500,000 tonne per year enterprise. However, whilst the demonstrated gain over-estimate is significant, the ranking of individuals within a population is virtually unchanged. Thus, the use of fixed economic weights is acceptable, providing the user understands that absolute gain may be overestimated at high selection intensities.

The defined objective (Chapter 3) is the minimisation of the cost of producing unbleached kraft pulp, yet the majority of unbleached kraft pulp produced in the world is bleached and used in paper manufacture. It is a shortcoming of this work that the objective is not defined in terms of the profitability of producing bleached paper, and implicit in the objective being specific to unbleached pulp is the assumption that none of the traits in the objective have influence on the costs of bleaching and paper making. There is some evidence that density and pulp yield may influence paper quality but the effects on profitability are less apparent (Higgins 1984, Ikemori *et al.* 1986, Arbuthnot 1991, Dean 1995). Further, other traits, such as fibre length, may be important for paper strength (Zobel and van Buijtenen 1989, Campinhos and Claudio da Silva 1990). Further work needs to be undertaken to understand the relationships between traits which can be measured such as density and fibre length, and the profitability of paper manufacture.

The production function developed in Chapter 3 has application not only in defining the appropriate breeding objective, but also as a general decision-making tool in forest management. When deciding between fertiliser regimes or different growing sites, if the *VOL*, *DENS*, *PY* and *FORM* associated with the different options can be measured, the economic value of each management option can be determined by substituting the trait values directly into the production function. For the purposes of demonstration, values for *VOL*, *DENS* and *PY* at rotation for Site 1 and Site 2 have been approximated from observed *dbh*, density, and pulp yield at age 7 years (Table 10.2) - whilst the accuracy of these approximations is questionable, they serve to demonstrate the application of the production function as a management tool. The values were substituted directly into the cost function (Eqn. 3.3) and the resulting pulp costs appreciated to rotation end at

15 years using a 5% discount rate. The costs of growing, harvesting, and transporting wood were assumed to be the same for both sites.

Table 10.2: Estimated *VOL*, *DENS*, *PY* and total pulp cost for Site 1 and Site 2.

	Site 1	Site 2	units
VOL	255	245	$m^3\ ha^{-1}$
DENS	0.465	0.535	$t\ m^{-3}$
PY	0.512	0.488	$t\ t^{-1}$
total pulp cost	465	440	$\$\ t^{-1}$

Site 1 is considered the more fertile of the two sites (Table 5.1) yet the predicted total pulp cost is higher for Site 1 than for Site 2 (Table 10.2) due to the considerably lower wood density on Site 1.

10.2 SELECTION SYSTEMS

The traits in the breeding objective, standing volume, basic density, pulp yield, and form, all at harvest, are rarely directly assessed. All are difficult to measure and direct measurement systems are relatively destructive to individual trees. Breeders need simple, non-destructive systems for assessing and predicting breeding objective traits which can be used cheaply and easily to assess large numbers of individuals.

Diameter at a fixed height of 1.3 or 1.4 m is commonly used as a selection trait for total stem volume (Cotterill and Dean 1990). Chapter 7 (Table 7.5) demonstrated a high genetic relationship between diameter at 1.3 m and total stem volume in seven-year-old *E. nitens* confirming the use of diameter in the indirect selection of volume.

Chapter 5 demonstrated the application of the Pilodyn in the indirect selection of basic density in eucalypt breeding programs. The Pilodyn showed a very high correlation with density (r_g = -0.92) and a given level of gain in density can be achieved at a lower assessment cost using Pilodyn over other methods of density assessment. However, the correlation lower

than unity means that the maximum gain in density achievable, using Pilodyn-based selection, falls short of the maximum gain achievable from more direct density assessment via extraction of disks or cores. Based upon the example presented in Figure 5.3, direct density assessment will achieve 10% more gain when all trees are assessed than the gain achievable through assessing all trees using Pilodyn, but at a considerably greater cost (approximately $10,000 in the presented example). Assuming an achievable gain in density (Table 4.5) of 0.04 t m^{-3}, and an economic weight for density of $349 t^{-1} m^3 (at the time of plantation establishment - Chapter 3), the present value of 10% of the achievable gain in density equates to $1.40 saving per tonne of pulp produced, or $700,000 for one year of a 500,000 tonnes-of-pulp-per-year operation. This clearly demonstrates that whilst Pilodyn does correlate well with density, the value of even small marginal gains in density far outweigh the greater cost of direct density assessment. It must be recognised, however, that resources are not automatically made available to tree breeders on the promise of future gains, and where funds for breeding are limited the Pilodyn provides a cheap and reliable assessment method for achieving significant gains in density.

Near Infrared Reflectance (NIR) analysis has shown promise in the indirect assessment of pulp yield and other wood chemistry traits of perceived commercial importance. Chapter 6 demonstrated that observed reflectance in some regions of the NIR spectra is heritable (Figure 6.1). The high repeatability of observed NIR reflectance (ρ = 0.9 - Table 8.3) shows the NIR system is a precise measurement technique and confirms that the current practice of taking two replicate observations per sample should provide sufficient prediction accuracy. The decline in repeatability at longer NIR wavelengths (Figure 6.1) leads to conclusion that wavelengths longer than 1850 nm should be excluded from analysis. Chapter 8 examined the application of NIR analysis for predicting pulp yield based upon small samples which could be collected as cores from standing trees. The NIR predicted pulp yields, however, showed poor agreement with values obtained from laboratory pulping assessments (Figure 8.3). Major doubts hang over the suitability of the calibration model used in the analysis and further work is currently underway towards the construction of a more appropriate calibration model (Appendix 8.1) which may improve the accuracy of NIR-based predictions.

10.3 EARLY AGE SELECTION

Predicting the optimum age for early selection, towards the breeding objective derived in Chapter 3, requires understanding of the accuracy of predicting breeding objective traits at ages earlier than harvest age.

The age-age genetic correlations for growth reported in Chapter 7 were not well described by Lambeth's (1980) linear relationship with the log of the ratio of ages (*LAR*). Of the three age-age correlations estimated, however, two were relationships between later-age diameter (*dbh*, at four and seven years) and early-age height (20 months). Other workers have observed height at one year to be a poor indicator of later-age growth performance (e.g. Lambeth 1980, Griffin and Cotterill 1988, Borralho *et al.* 1992a). Results presented in Chapter 7 suggest that height at 20 months is similarly a poor indicator of later growth. For the determination of optimum early selection age, the questionable reliability of the age-age correlations with early-age growth reported in Chapter 7 lead to these being discarded in favour of age-age relationships reported for a (more complete) study of *E. grandis* (Van Wyk 1990).

On the other hand, Chapter 7 demonstrated age-age correlations in basic density to be very high, and that observed correlations were well described by Lambeth's (1980) relationship with *LAR*. The results were derived from cores taken 2.5 metres from the ground and thus the applicability of the conclusions to the expected age-age relationships for whole-tree density require confirmation. However, the very high correlations between density measured on disks cut from 1.3 m and disk and core densities predicted from the 2.5 m (height) density measurements (both $r_g = 0.98$), and the apparent strong relationship between 1.3 m density and whole-tree density reported in Chapter 5 (Figure 5.1), are indicators of the robustness of the conclusions.

The genetic correlation between the pulp yield of wood deposited in the third and seventh years after plantation establishment was explored in Chapter 8 using NIR analysis techniques. Whilst the observed age-age genetic relationship was a high 0.72, the poor agreement between the NIR predicted pulp yields and the values obtained via laboratory pulping lead to the conclusion that the observed age-age relationship may be of little relevance in early selection for pulp yield.

As selection for density and growth was demonstrated in Chapter 3 to achieve 95% of the gain expected from selection for density, growth, pulp yield, and form, Chapter 9 determined the optimum age for early selection for growth and density towards the breeding objective developed in Chapter 3. For a harvest age of 15 years, the optimum *biological* selection age (the selection age where average annual gain is maximised) was four years, whilst the optimum *economic* selection age (the selection age where the present value of all future gains is maximised) was three years. In operational breeding programs, selection for growth rate is considered to be reliable at four years (Borralho *et al.* 1992b), whilst reliable selection for wood properties such as density must wait until six years[1]. Chapter 9 demonstrated the converse to be true: that later-age density can be reliably assessed earlier than can later-age growth.

Whilst delaying selection age from four to six years does not greatly reduce the average annual gain (a two year delay equates to a 4% reduction in average annual gain - Figure 9.1), delaying the realisation of gain has a more significant effect upon the economic value of breeding (a two year delay from four to six years equates to an 11% reduction in economic value - Figure 9.2). Thus, for an enterprise producing 500,000 tonnes of pulp annually, the net present value of selecting at four years rather than six years is approximately $30M.

If early selection for density is based upon Pilodyn penetration (Chapter 5) the optimum biological selection age increases to five years (Table 9.2) due to the lower age-age correlations for the density of the outer-most wood (Figure 7.4). The optimum economic selection age remains unchanged at three years.

10.4 RELATIONSHIP BETWEEN DENSITY AND GROWTH

The genetic relationship between growth and density was observed to be low but unfavourable (r_g = -0.2, Table 7.5), however the stronger observed relationship between the density of the outer-most growth ring and tree

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[1]Phil Whiteman, Technical Manager, Australian Paper Plantations Pty. Ltd., Morwell, Australia

volume (r_g = -0.5, Table 7.5) suggests that the unfavourable relationship may become stronger at later ages (reported genetic correlations between growth and density in plantation eucalypts range from -0.1 to -1.0 - see Chapter 7).

Most analysis reported in this thesis involves samples collected from 50 families selected from a total of 94 families on the basis of growth performance. This selection on the basis of growth rate would have resulted in reduced additive variance for growth in the selected population, with the magnitude of the reduction defined by the accuracy of selection (heritability). The variance of traits showing correlation with growth would have also been reduced in the selected population, with the magnitude of reduction defined by the degree of correlation between growth and the correlated traits (Villanueva and Kennedy 1990). Whilst the relevance of these effects cannot be defined from the results presented here, the heritability for growth in temperate eucalypts may be low to moderate (e.g. h^2 of 0.18 reported by Dean *et al.* 1990, >0.4 reported in Chapter 7), and the relationship between growth and density also low (r_g of -0.22, Dean *et al.* 1990, -0.2 reported in Chapter 7). As more than 50% of families were sampled, the effect on results presented here is assumed to be small, and influence on conclusions negligible.

As accurate estimates of the true genetic relationship between density and growth are still unavailable, a sensitivity analysis of the importance of the relationship on the relative value to breeding of the four traits in the breeding objective (Chapter 3) was conducted. The relative value to breeding of standing volume, basic density, pulp yield, and form (after Chapter 3) in relation to the assumed genetic correlation between density and volume production is depicted in Figure 10.1.

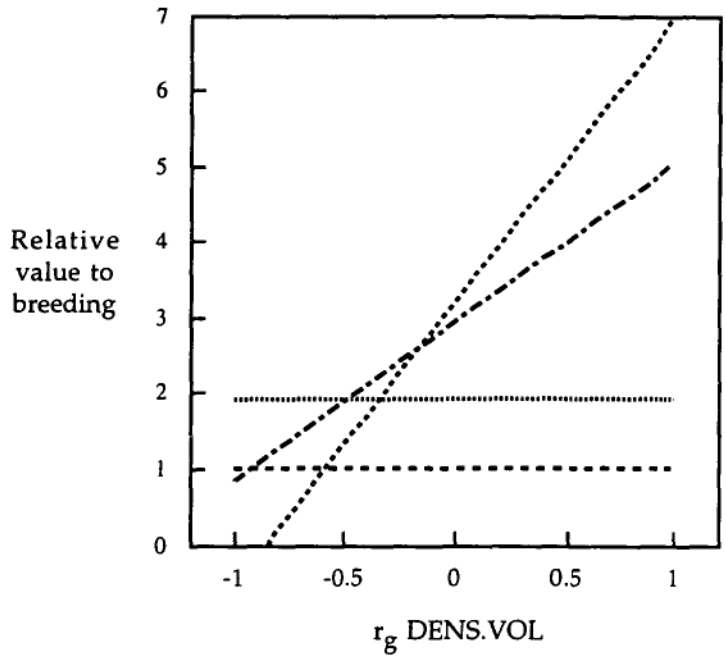

Figure 10.1: The relative importance to breeding (after Eqn. 3.9) of *DENS* (.....); *VOL* (-.-.-.); *PY* (.....); and *FORM* (- - - -) versus the genetic correlation between density and volume production (r_g DENS.VOL). Relative value is expressed in relation to the relative value of *FORM*, i.e. a value of 3.5 equates to the trait being 3.5 times as important as *FORM*. All other parameters held constant (Table 3.2).

It is clear that conclusions regarding the relative value of each trait to breeding is sensitive to the assumed genetic relationships between traits in the objective. The conclusion that density and volume production are the most important traits in breeding eucalypts for kraft pulp holds where the relationship between density and growth is positive or weakly negative ($+1.0 > r_g > -0.3$).

Conclusions

In General

The production function defined in this thesis will provide considerable insight into the economic implications of tree improvement. It has wider application to plantation forest management - to, for example, the selection of sites or the selection of optimum fertiliser regimes. Whilst further improvements are clearly needed, the better definition of the breeding objective allows industrial tree growers to look hard at their processes in the quest for higher quality plantation forestry.

The confirmation that diameter at 1.3 metres is well correlated with total stem volume is useful if only to confirm current assumption. The application of the Pilodyn in the early selection of density provides tree breeders with a quick, cheap, reliable, and relatively non-destructive assessment system. And the near infrared analysis system may still provide a similarly effective system for assessment of pulp yield.

The optimum age for early selection is three or four years, and there is considerable economic benefit to be derived from selecting at four years rather than the currently assumed optimum of six years.

More Specifically

- For a new mill, the cost of converting green roundwood to unbleached pulp, expressed in dollars per oven-dry tonne of unbleached pulp, will decrease with increasing density and pulp yield. Pulping cost ($C_{pulping}$) as a function of density ($DENS$) and pulp yield (PY) can be approximated by:

$$C_{pulping} \propto \frac{1}{(DENS)^{0.5}(PY)^{0.7}}$$

- The key traits which influence the total cost of producing unbleached eucalypt kraft pulp (from establishing and growing plantations, through harvesting and log transport, chipping and pulping) are density and standing volume at harvest, accounting for 95% of the gain possible using a selection criterion involving density, volume, pulp yield, and stem form.
- Selection for pulp yield alone provides approximately 50% of the gain possible from selection for either density or standing volume alone. Stem-form has only minimal effect on the total cost of producing pulp.
- There is observable non-linearity between total pulp-cost and the levels of all traits in the breeding objective cost function, and the true economic weight for each trait declines at higher values of each trait.
- The breeding objective function shows interdependence between traits in the objective - that is, the economic weight for one trait is dependent upon the actual value of other traits.
- The error associated with applying a cost function via the use of economic weights is greater at high selection intensities: when the best 1% of a population is selected expected gain may be over-estimated by 25%.
- An alternative method of gain determination is proposed: predicted values of selection traits are used to generate values for breeding objective traits which are then substituted directly into the breeding objective cost function thus avoiding errors associated with non-linearity and interdependence.
- Individual Pilodyn penetration and 1.3 m disk density showed relatively high heritabilities of 0.60 and 0.73 respectively.
- The heritability of Pilodyn penetration and its correlation with density was aspect dependent.
- The repeatability of Pilodyn observations was very high (0.90) and two observations per tree were sufficient for indirect density selection (providing 94% of the maximum possible selection accuracy for multiple observations). Two Pilodyn observations on the west aspect (the aspect shown to be most favourable in this study) gave a

heritability of 0.62, a genetic correlation with density of -0.96, and an efficiency of indirect selection for density of 84%.

- Whilst Pilodyn assessment of density will not yield as much gain in density as direct density selection, Pilodyn assessment is considerably cheaper and a much higher selection intensity can be achieved with Pilodyn selection for a given cost of assessment.
- Heritability of near infrared reflectance across the 1100 - 2500 nm spectrum ranged from 0 to 0.35.
- Repeatability of near infrared reflectance was consistently greater than 0.7 for wavelengths shorter than 2250 nm, but showed decline at longer wavelengths to a low 0.3 at 2500 nm.
- Age-age correlations for density were consistently high and declined with increasing age difference.
- Age-age correlations for growth were less conclusive and more work is required to clarify the observed trends.
- Density appears to be weakly and negatively related to growth in *Eucalyptus nitens* at age seven years (r_g = -0.2).
- In selection for density and growth towards reducing the cost of producing unbleached kraft pulp in eucalypts, the optimum *biological* selection age (the selection age where average annual gain is maximised) was four years, whilst the optimum *economic* selection age (the selection age where the present value of all future gains is maximised) was three years. These conclusions are robust to changes in assumptions of trends in genetic parameters and interest rates used in analysis.

THE END

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